INFLUENCE OF PLANTING DEPTH ON LANDSCAPE ESTABLISHMENT OF CONTAINER-GROWN TREES

A Dissertation

by

DONITA LYNN BRYAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2008

Major Subject: Horticulture

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Approved by:

Chair of Committee,	Michael A. Arnold
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ABSTRACT

Influence of Planting Depth on Landscape Establishment of Container-Grown Trees.

(December 2008)

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Chair of Advisory Committee: Dr. Michael A. Arnold

Tree transplanting practices influence plant survival, establishment, and subsequent landscape value. The inability to adequately quantify effects of inappropriate tree planting and transplanting practices threatens long-term viability and productivity (sustainability) of trees within terrestrial ecosystems. Tree planting depth, i.e. location of the root collar relative to soil grade, is of particular concern for tree growth, development, and performance in the landscape. A series of model studies was conducted to investigate effects of planting depth, container production methods, and transplanting practices on landscape establishment of container-grown trees. Studies included determining the effect of planting depth and soil amendments on live oak (*Quercus virginiana* Mill.) and baldcypress (*Taxodium distichum* (L.) L. Rich.), the effect of planting depth during container production and subsequent landscape establishment of lacebark elm (*Ulmus parvifolia* Jacq.), the effect of planting depth and irrigation practices on landscape establishment of sycamore (*Platanus occidentalis* L.), and the effect of planting depth and transplant season on landscape establishment of baldcypress. Optimum planting depth varied among species and was dependent on cultural practices and/or environmental conditions. Overall, live oak and baldcypress growth was better when planted with root collars at grade in sand in raised beds compared to planting below grade in control soils. Lacebark elm growth was greater when planted at grade during the initial container production phase and below grade in the second container production phase. Subsequent landscape establishment was variable, but planting at grade to 5 cm above grade produced greater growth. Sycamore trees planted below grade had increased mortality and decreased growth compared to trees planted at grade or above grade, while irrigation had no effect. Baldcypress planted above grade had reduced growth compared to those planted at or below grade, while transplant season had no effect. Species and cultivars within species may differ markedly in their response to environmental/cultural stresses, including planting depth. Each tree species originating from a specific environment may represent an ecotype adapted to that particular environment. Therefore, tree survival and performance may depend on the difference between the environment from which the tree was grown and the experimental system into which it is introduced.

DEDICATION

This dissertation is dedicated to my parents, family, and friends for all of their help, support, and encouragement.

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CHAPTER I
INTRODUCTION AND LITERATURE REVIEW

Root Growth

The development of a root system capable of anchoring the shoot and obtaining sufficient water and nutrients is essential to survival of most terrestrial plants. Generally, the finer, most external roots are the roots that are responsible for nutrient and water uptake, while coarser, higher order roots provide the framework for nutrient and water transportation and the strength needed to anchor trees (Eissenstat and Yanai, 1997). Vegetation types differ in total and fine root biomass, root turn-over, vertical root distributions, and maximum rooting depth (Canadell et al., 1996; Stone and Kalisz, 1991; Vogt et al., 1996). Because of their function and higher turnover rates, fine roots strongly influence soil, carbon, water, and nutrient fluxes in the landscape (Eissenstat and Yanai, 1997; Gill and Jackson, 2000). Globally, >90% of all soil profiles had at least 50% of all roots in the upper 0.3 m of the soil profile (including the organic horizons) and 95% of all plant roots are in the top 2 m of the soil profile (Schenk and Jackson, 2002; Schenk and Jackson, 2005). Deeper rooting depths are usually associated with water-limited conditions (Schenk and Jackson, 2002; Schenk and Jackson, 2005). Rooting depth was also reported to decrease as depth of organic horizons increased (Schenk and Jackson, 2002). In addition, the soil strength/resistance that a root can penetrate is determined by the maximum turgor pressure generated within the elongation zone of the root, and the shape and frictional characteristics (tolerance) of the root tip (Bengough et al., 1997; Grant, 1993; Kozlowski, 1999; Passioura, 1991; Siegel-Issem et al., 2005). Therefore, various physical and biological factors, including soil temperature, moisture, oxygen, and bulk density, may limit root growth, development, and nutrient uptake (Kaspar and Bland, 1992; Cook et al., 2007), which in turn affect plant growth, performance, and landscape establishment.

This dissertation follows the format and style of the Journal of the American Society for Horticultural Science.

SOIL TEMPERATURE

Soil temperature significantly affects root growth and development (Alvarez-Uria and Korner, 2007; Boone et al., 1998; Bouma et al., 1997; Fitter et al., 1998; Pregitzer et al., 2000) as well as microbial processes that release nutrients (Lloyd and Taylor 1994; Fitter et al. 1998; Rustad et al., 2001), and thus is a key component of plant growth and performance in the landscape. However, it is difficult to distinguish the direct effect of temperature on root growth from the numerous indirect effects that temperature can have on abiotic and biotic factors that influence root growth and development. For example, higher temperatures increase evapotranspiration and thus lead to lower soil water availability. In addition, higher seasonal temperatures are generally associated with periods of higher radiation input and thus often temperature effects on root growth are confounded with radiation effect on root growth (Edwards et al., 2004). Just as temperature affects many environmental variables, soil temperature itself varies with air temperature, radiation input, soil albedo, soil water content, and soil depth. Many factors influence changes in soil temperature including season, diurnal air temperatures, shading effect, soil moisture content, and depth. Most root growth, depending on species, occurs at temperatures from 19 to 28 °C, although there may be some ecotypic variation in plant response (McMichael and Burke, 2002). McMichael and Burk (2002) and Marschner (1995) reporteded that if soil temperatures drop below optimum, the structure and function of the root system may be altered such that the root system is smaller, less branched, and uptake of nutrients and water may be reduced. Root tolerance to cold or freezing temperatures is thought to be related to leakage or exudation of electrolytes (Sattin and Linderstrom, 1999) and/or abscisic acid synthesis (Marschner, 1995; McMichael and Burke, 2002). Conversely, when soil temperatures are above optimum, root growth and enzymatic activity are adversely affected (McMichael and Burke, 2002) via reductions in root length and lateral branching. Furthermore, Eidsten and Gislerød (1986) demonstrated that relatively short (30 min) exposures to high temperatures (≥ 30 °C) reduced root growth. In addition, it was noted that low daily average root zone temperatures did not compensate for damage caused by the short period of high temperature.

SOIL MOISTURE AND OXYGEN CONTENT

If soil temperature is not a direct limiting factor, deficient soil moisture may decrease root growth, although roots are usually capable of resuming growth after rainfall or irrigation events (Eissenstat et al., 1999; Gilman, 1990). Root respiration was reported to be reduced in dry soils (Bouma and Bryla, 2000; Bryla et al., 1997; Bryla et al., 2001; Eissenstat and Yanai, 2002; Marschner, 1995) where root respiration was only 10-20% of that in wet soils. Lack of soil moisture may also affect nutrient acquisition by roots from the soil due to its effect on diffusion and transpiration rates (Marschner, 1995). Low soil water content decreases root elongation (mechanical impedance of soil increases) and thus decreases nutrient acquisition and uptake (Marschner, 1995). At low soil moisture, K and P uptake is decreased and Ca and Mg uptake may be increased. However, Mackay and Barber (1985) reported that root hair growth is increased at low soil moisture content, and this may compensate for any decrease in root elongation and loss of access to less mobile nutrient pools. Some plants have roots that can withstand long drought periods, for example, Eissenstat et al., (1999) reported that roots of sour orange (*Citrus aurantium* L.) that were exposed to dry conditions for >40 days, fully recovered and were able to take up water and P within 24 hours after rewetting. The well developed exodermis on citrus roots may explain this root recovery (Huang and Eissenstat, 2000). Other species, such as wheat, were reported to need to develop new roots before water and nitrate uptake resumed (Brady et al., 1995).

Proper root growth and function is dependent on oxygen which increases when the proportion of non-capillary pores increases (Mathers et al., 2007). Capillary pores (< 0.3 mm) are responsible for retaining the majority of water after an irrigation or rainfall event, while non-capillary pores (> 0.3 mm) retain only small amounts, thus increasing aeration (Argo, 1998). Irrigation or precipitation events fill soil pores with water and displace air from the pores. Compaction leads to an increase in the proportion of capillary pores and thus increases the proportion of pores that remain filled with water longer, thus reducing oxygen flow to roots for prolonged periods, which in turn limits root growth (Pokorny, 1987). Water and the solid matrix in soils slow diffusion of oxygen and reduce soil oxygen concentration (Armstrong and Drew, 2002). Oxygen levels are usually suboptimal in most soils since many of the capillary pores remain filled with water instead of air. Kozlowski and Davies (1975) reported that oxygen content in upper levels of drained soil lies approximately between 2 and 10%. A soil oxygen content of 3% or less is reported to stop root growth in most plants (Kozlowski and Davies, 1975). Drew (1988) reported that low oxygen concentrations in the soil strongly inhibit root nutrient uptake and transport to the shoots, including N, P, and K. However, Else et al. (1995) reported an increase in xylem sap phosphate in flooded tomato (*Solanum exculentum* Mill.) plants, possibly due to the release of P from oxygen starved or injured root cells. Low oxygen content in soils decreases Na efflux and results in an increase in transport of Na to shoots while K transport is inhibited (Armstrong and Drew, 2002), which may result in an interference with regulation of the stomates (Devitt et al., 1984). Roots that are oxygen deficient have reduced indoleacetic acid, gibberellins, and cytokinin synthesis (Reid and Bradford, 1984) and enhanced xylem sap abscisic acid (Zhang and Davies, 1987). The subsequent increase in foliar abscisic acid results in reduced stomatal conductance and reduced leaf growth in flooded conditions (Bradford and Hsiao, 1982; Sojka and Stolzy, 1980) Other plants reduce root oxygen starvation problems via formation of extensive stem and root aerenchyma which decreases resistance to oxygen flow down to the roots (Armstrong and Drew, 2002).

Pirone (1972) reported that roots of baldcypress (*Taxodium* (L.) Rich.) have low oxygen requirements, and are very tolerant to low soil oxygen. Roots of elm (*Ulmus* L.) and sycamore (*Platanus* L.) were also reported to be tolerant or able to avoid injury as a result of low soil oxygen, while roots of some species of oak (*Quercus* L.) are readily damaged as a result of low soil oxygen. The extent of damage to roots as a result of low soil oxygen was suggested to be dependent on a number of interacting factors, including:

plant species, soil bulk density, total pore space, water retention and air-filled porosity, and duration of low oxygen event (Kozlowski and Davies, 1975; Pirone, 1972).

Container Production

Landscape trees are increasingly being produced in container nursery systems (USDA, 2004). USDA (2004) reported that 45%, 58%, and 85% of deciduous shade, coniferous evergreen, and broadleaf evergreen trees, respectively, were produced in containers in 2003. Container production of landscape trees has many advantages over traditional field grown practices (Mathers et al., 2007). There is less damage to the root system at transplanting from containers compared to balled and burlapped trees which potentially results in better transplant quality and establishment, and reduced mortality rate (Mathers et al., 2007). Gilman (1988) reported that less than 10% of initial total root length was located in the root ball of dug trees. Thomas (2000) reported that many fine roots (comprising 30% of total root area) are left behind in dug trees. However, Blessing and Dana (1987) reported that transplanted field-grown juniper (*Juniperus chinensis* L.) had greater root spread and root dry mass when compared to transplanted container-grown juniper. Tree container production is less labor intensive at harvest than traditional field production as containers are easier to handle and transport (Mathers et al., 2007; Whitcomb, 1984). Moreover, trees sold in containers are more marketable because the product appeals to consumers and landscapers alike, and trees in containers may be sold and planted year round (Mathers et al., 2007).

We suggest that trees are frequently planted inappropriately during container production as a result of numerous interrelated nursery practices, including; 1) inappropriate size of plant material to container size ratio at up-canning, 2) shrinkage and loss of substrate, 3) excessive filling of container and compaction of substrate, 4) inappropriate irrigation practices, 5) hiding graft union, pruning scars, and 6) general carelessness. Most container substrates (pine bark/sand) have low bulk density (0.17-0.19 $g \cdot cm^{-3}$) and adequate air space at transplant, but after handling, irrigation, settling, back-filling, and time, the bulk density tends to increase (0.32 $g \cdot cm^{-3}$) which can negatively affect root growth (Bilderback et al., 2005). In addition, container production has the potential to produce trees with stem girdling roots, depending on the production schedule, container type, and/or cultural practices (Mathers et al., 2007; Maynard et al., 2000).

Tree Transplanting Practices

Trees have environmental, economic, cultural, and aesthetic landscape value (Perkins and Heynen, 2004; Summit and Sommer, 1998). However, the inability to adequately quantify the effects of inappropriate tree planting and transplanting practices threatens the long-term viability and productivity (sustainability) of trees within terrestrial ecosystems. Transplanting practices vary substantially among firms and individual practitioners (arborists, foresters, horticulturists, and other professionals) (TCIA, 2005; Watson and Himelick, 1997). Harris and Bassuk (1993) suggested that transplanting success relies on interactions among the tree's health at time of transplanting, climate, micro-climate, soil conditions, and post-transplant care, as a result, research reports are often conflicting.

At transplanting and during landscape establishment trees are prone to water deficits as a result of decreased root growth and development, which result in decreased ability for roots to absorb soil moisture (Haase and Rose, 1993; Rietveld, 1989). On the other hand, leaf area reduction from pruning/leaf drop decreases respiration/transpiration and may diminish the negative effect of low soil water deficits on root growth and development (Struve and Joly, 1992). Harris et al. (1994) suggested that a fibrous root system enhances planting/transplanting success and landscape establishment as there are generally more intact roots tips and a larger surface area for water absorption/soil exploration. Arnold and Struve (1989) reported that intact lateral roots of green ash (*Fraxinus pennsylvanica* Marsh.) seedlings began extension in ≤ 7 d after transplanting, whereas severed roots required approximately 17 d to regenerate new root tips. In addition, root diameter may also affect the regeneration of root tips. Severed smaller diameter roots were reported by Struve and Rhodus (1988) to regenerate root tips faster than larger diameter roots, and the number of roots regenerated increased as root diameter decreased (Lee and Zieslin, 1978).

SOIL AMENDMENTS

Soil conditions are of particular importance for tree planting/transplanting success in urban environments. Important soil conditions to consider during planting/transplanting include pH, texture, organic matter composition, and/or location of soil nutrient pools (Consolly, 2007). These factors may interact to affect soil structure, water-holding capacity, aeration, drainage, nutrient availability or toxicity, and thus root penetration and growth (Schenk and Jackson, 2002). A common practice to improve existing soil conditions at transplanting is the incorporation of organic and/or inorganic amendments to improve the physical, chemical, or biological properties of the soil (Bunt, 1988; Harris and Bassuk, 1993; Scheiber et al., 2007), including water use efficiency or availability (Pausas et al., 2004). However, these soil amendments may vary widely in their composition and effectiveness, depending on type, source or location (Bunt, 1988; Consolly, 2007; Scheiber et al., 2007). Furthermore, these amendments, both organic and inorganic, are usually applied as a shallow layer on top of and/or shallowly incorporated into the upper layer of the 'native' soil, which may disrupt the continuity of the existing soil profile, and result in the formation of a perched water table (Bunt, 1988). A perched water table would prevent 'normal' drainage, make the rhizosphere wetter after irrigation or rainfall events, than it would be otherwise, potentially resulting in poor aeration (low soil oxygen levels), after each rainfall or irrigation event. Conversely, under conditions of high evapotranspiration, the plant may be subjected to a shortage of water, as the roots have not been able to grow deeper into the soil profile. In addition, organic amendments, such as peat, may decay overtime, potentially resulting in enhanced soil nutrient availability/toxicity, particularly nitrogen (Bunt, 1988). However as the organic amendment decays it may also reduce its total pore space and/or reduce the number of large air-filled pores, resulting in poor aeration and drainage issues overtime (Bunt, 1988).

TRANSPLANT TIMING

The season in which trees are transplanted may affect growth, survival, and landscape establishment. It has been suggested that in most temperate locations, transplanting in spring or autumn provides ideal climatic and soil conditions, as root growth is better when the soil is warm and moist and trees have not started to actively grow (Richardon-Calfee and Harris, 2005). However, transplanting in autumn could result in low survival as a result of low physiological potential for root regeneration at this time of year (Larson, 1984) and/or due to the roots inability to grow at relatively cool soil temperatures (Jenkinson, 1980), although this may vary depending on climate (hardiness zones). Alternatively, transplanting in spring when trees are starting to actively grow may result in excessive carbohydrate drain from roots (Dumbroff and Webb, 1978). Richardson and Calfee et al. (2007) reported that with proper maintenance of soil moisture, fall and spring transplanting resulted in similar root regeneration as summer planting/transplanting of sugar maple (*Acer saccharum* Marsh.). Similarly, Harris et al. (2001) reported that with proper irrigation, fall or spring transplanting resulted in similar growth (height and diameter) and root length accumulation in Turkish hazelnut (*Corylus corurna* L.). Shoemake and Arnold (1997) reported that fall transplanting resulted in better growth and survival of sycamore (*Platanus occidentalis* L.) than spring transplanting which in turn was better than summer transplanting. However, low survival of autumn-transplanted seedlings in cold temperate climates has been related to low physiological potential for root regeneration at that time of year (Larson, 1984), and the inability of new transplants to grow roots in cold soils (Jenkinson, 1980).

IRRIGATION

During tree transplant establishment, soil water content is suggested to be a determining factor for plant growth and survival (Gilman, 1990; Kozlowski and Davies, 1975). The volume, frequency, and duration required depends on numerous factors. Gilman et al. (1998) reported that when container-grown live oaks (*Quercus virginiana* L.) were transplanted into the field (Millhopper fine sand), growth (height, trunk diameter, foliage spread, and stem water potential) and survival after 27 months were not affected by irrigation volume (11-L, 22-L, or 33-L), rather irrigation frequency (frequent irrigation - daily for 13 weeks, then once every 2 days for 8 weeks, then weekly for 11 weeks, then no irrigation for 30 weeks; infrequent irrigation - daily for 2 weeks, twice a week for 8 weeks, weekly for 3 weeks, and then no irrigation) was found to be more important, in that frequent irrigation enhanced transplant establishment, growth, and survival compared to infrequent irrigation. Red maples (*Acer rubrum* L.) which were subjected to frequent irrigation (daily for 9 weeks, then once every 2 days for 15 weeks) after transplanting had greater trunk diameter, increased root number, root diameter, and uniform root distribution after 5 years, when compared to trees irrigated less frequently (daily for 1 week, biweekly for 2 weeks, every third day for 6 weeks, every 10 days for 10 weeks, and then no irrigation) (Gilman et al., 2003). Similarly, container-grown live oaks which were frequently irrigated (7.6-L 3 times per week for 38 weeks) after field transplanting grew twice as fast (diameter and height) in the first growing season as trees which were infrequently irrigated (7.6-L approximately every 10 days for first 3 months) (Gilman, 2004). However, in the second season, similar growth rates were reported regardless of irrigation treatment, possibly as a result of full tree establishment. Therefore, irrigation practices including frequency are important for initial tree survival at transplant.

PLANTING DEPTH

Variability in planting depth is of particular concern to plant growth and landscape performance, specifically the location of the root collar and thus the root system, relative to the soil grade, as optimum planting depth may vary among species, and may be dependent on cultural practices and/or environmental conditions (Arnold et al., 2005; Ball, 1999; Browne and Tilt, 1992; Drilias et al., 1982; Gilman and Grabosky, 2004; Pirone et al., 1988). Furthermore, the fate of trees under these conditions is inconsistent and not well understood (Watson and Hewitt, 2006).

Arnold et al. (2005) reported that when container-grown bougainvillea goldenraintree (*Koelreuteria bipinnata* Franch.) were transplanted into the field (Boonville fine sandy loam) with the root collars 7.6 cm below grade, at grade, or 7.6 cm above grade, a 62%, 57%, and 17% mortality rate, respectively was reported 2 years after transplanting. Arnold et al. (2007) reported that container-grown green ash (*Fraxinus pennsylvanica* Marsh.), sycamore (*Platanus occidentalis* L.), crapemyrtle (*Lagerstroemia indica* L. x *Lagerstroemia fauriei* Koehne. 'Basham's Party Pink'), oleander (*Nerium oleander* L. 'Cranberry Cooler') and vitex (*Vitex agnus-castus* L. 'LeCompte') transplanted into field (Boonville fine sandy loam) soil with the root collars 7.6 cm below grade were adversely affected with survival and growth severity varying among species. A mortality rate of 33% (crapemyrtle), 50% (green ash), 33% (oleander), 50% (sycamore) and 0% (vitex) was reported 3 years after transplanting with root collars 7.6 cm below grade. Transplanting root collars at grade or 7.6 cm above grade resulted in 0% mortality for all species except for the sycamore planted at grade which resulted in 17% mortality (Arnold et al, 2007). Growth (height and trunk diameter) was similar in species planted at grade and 7.6 cm above grade except for sycamore which had a significantly greater height and trunk diameter when planted 7.6 cm above grade compared to planting at grade. Planting root collars 7.6 cm below grade reduced height and trunk diameter in all species apart from sycamore (Arnold et al, 2007). Sparks (2005) reported that field-grown pecan (*Carya illinoinensis* (Wangenh.) K. Koch) trees (3 year old orchard) with graft union set at 6 cm to 18 cm below grade had problems with trunk tilt, and trees set with graft union at 20 to 34 cm below grade blew over as a result of high winds (maximum sustained 54 to 70 $km{\cdot}hr^{-1}$).

Wells et al. (2006) reported that when balled-and-burlapped Yoshino cherry (*Prunus* x *yedoensis* Matsum.) were planted with root flare at 15 cm or 31 cm below grade, a 50% mortality rate was reported 2 years after transplanting, while trees planted with root flare at grade survived. The occurrence of girdling roots was influenced by planting depth in red maple (*Acer rubrum* L.) with 14%, 48%, and 71% occurrence on trees planted at grade, 15 cm below grade, and 31 cm below grade, respectively (Wells et al., 2006). When planted 31 cm below grade, Yoshino cherry and red maple had significantly lower chlorophyll content as estimated by SPAD meter readings (Wells et al., 2006). This was suggested to have been due to reduced water infiltration to the root ball at depth and insufficient access to shallow mineral nutrient pools (Wells et al., 2006).

Broschat (1995) reported that when container-grown pygmy date palm (*Phoenix roebelenii* O'Brien) were transplanted into the field with the original root ball 90 cm below grade, a 60% mortality rate was reported 15 months after transplanting, while pygmy date palms with original root ball planted at grade survived. When planted 90 cm below grade, pygmy date palms had much higher foliar Mg and Fe (Fe possibly due to the vicinity of the water table increasing the Fe solubility) concentrations compared to those at planting depths ranging from 0 to 60 cm below grade (Broschat, 1995). As planting depth increased, foliar Mn concentrations decreased consistently, due to the increased uptake of Fe possibly inhibiting the uptake of Mn (Broschat, 1995). Goss et al. (1990) and Armstrong and Drew (2002) reported that if oxygen partial pressure decreased below a certain level in the soil, as would be expected with increasing depth and/or reduced pore size, root growth and function is often impaired by anoxic conditions. Under these conditions mobility of certain nutrients increases, specifically Fe and Mn, to potentially toxic levels, depending on the plant species.

Description and Importance of Experimental Plant Species

Within urban areas, soil and environmental conditions vary substantially from location to location. Tree selection, therefore, should be made on the basis of the conditions and potential stresses present at the site (Berrang et al., 1985). Furthermore, it is also important to note that plant species and cultivars within species may differ markedly in their response to environmental/cultural stresses. Each tree species originating from a specific environment may represent an ecotype adapted to that particular environment. Therefore, tree survival and performance may depend on the difference between the environment from which the tree was grown and the experimental system or landscape site into which it is introduced. Thus, the plant species live oak (*Quercus virginiana* Mill.), baldcypress (*Taxodium distichum* (L.) L. Rich.), sycamore (*Platanus occidentalis* L.), and lacebark elm (*Ulmus parvifolia* Jacq.) were selected based on their horticultural, landscape, and aesthetic values, and their broad tolerance to adverse urban conditions for use in model studies on planting depth.

QUERCUS

The genus *Quercus* L. belongs to the family Fagaceae Dumort. and includes approximately 450 species of monoecious, deciduous, or evergreen trees native to northern temperate zones, and some subtropical/tropical zones at high elevation as well as south to Columbia and to Malay Archipelago (Bailey and Bailey, 1976; Manzanera et al., 1996). The genus is wide spread in North America and Europe. *Quercus spp.* leaves are alternately arranged, with dentate, serrate, or pinnately lobed margins. The male flowers (catkins) and female flowers (spikes) are one to many, and the fruit is an acorn (nut enclosed or surrounded at base by a cuplike involucre) (Bailey and Bailey, 1976). *Quercus spp.* chromosome number is 2n=24, (Armstrong and Wylie, 1965; Duffield, 1940). Bark characteristics vary among species ranging from papery (flaky) to scale-like (not flaky), deeply furrowed to shallowly grooved to smooth, and light grey or brown to dark grey/black in color (Arnold, 2008).

Quercus spp. are considered to be a foundation genus, in that they may control population and community dynamics, and thus may modulate ecosystem processes (Ellison et al., 2005; McShea et al., 2007), an important consideration for urban forestation. *Quercus spp.* are also grown for their ornamental value, contribution to the landscape in urban and rural environments, and commercially is one of the most important temperate timber trees (Bailey and Bailey, 1976). The timber is heavy, hard, strong, tough, supple yet durable, and of considerable beauty (Bailey and Bailey, 1976; Tudge; 2006). The timber was formerly used in the construction of ships, buildings, and mines (pitprops) (Bailey and Bailey, 1976; Tudge, 2006), and has been used in the production of charcoal (Campbell-Culver, 2006). Oak timber is still favored for furniture, flooring, interior finishes, and fine veneers (Tudge, 2006). The timber is much prized by wine, sherry, and whiskey makers for the construction of barrels, casks and tubs (Campbell-Culver, 2006; Tudge, 2006). The wood burns well, and is essential for smoking and curing of foodstuffs (fish and cheese) (Tudge, 2006). The sap of some species may be extracted for a variety of medicinal uses, including prevention and/or cure of fever and urinary tract infection (Campell-Culver, 2006). The bark of some species yields dye, tannins, and cork (Bailey and Bailey, 1976; Tudge, 2006). Acorns produced by *Quercus spp.* are an important wildlife food resource in hardwood ecosystems (Martin et al., 1961; McShea et al., 2007), and may be suitable forage for pigs (*Sus spp.* L.) (Campbell-Culver, 2006; Cantos et al., 2003). In some parts of the world (including Spain, Italy, Korea, China, and Japan), acorns are utilized for human consumption (McShea et al., 2007). The U.S. Department of Agriculture National Nutrient Database indicates that acorns of some species of *Quercus* are a good source of vitamins, minerals, and are considered to be calorie dense (U.S. Department of Agriculture, 2008). Some acorns are reported to have high antioxidant activity due to the high levels of hydrolyzable tannins (Cantos et al., 2003).

Quercus virginiana Mill. (live oak) is a slow growing and long-lived tree, of considerable character, much desired for roadside and ornamental plantings (Texas Forest Service, 1971). Its distribution ranges from Virginia south to Florida and Mexico

(Bailey and Bailey, 1976; Texas Forest Service, 1971). It is an evergreen (semi-evergreen) tree, up to 18 m tall with a dense round topped crown and somewhat spreading habit (nearly horizontal branching) (Bailey and Bailey, 1976; Grimm, 1962; Texas Forest Service, 1971). The bark on the trunk and larger branches is dark brown tinged with red, and slightly furrowed to scaly in appearance (Texas Forest Service, 1971). Leaves are shiny, dark green, thick, leathery, elliptic to oblong, and are approximately 13 cm in length with entire (usually) margins (Bailey and Bailey, 1976). Acorns are relatively small (2 cm by 0.75 cm), oblong, and dark brown when mature (usually at the end of the first season) (Bailey and Bailey, 1976; Texas Forest Service, 1971). The acorn cup is tomentose, light reddish brown in color, and encloses approximately half of the nut (Bailey and Bailey, 1976; Texas Forest Service, 1971).

TAXODIUM

The genus *Taxodium* Rich. belongs to the family Cupressaceae Bartl. and includes approximately three species of deciduous trees in Eastern North America and Mexico (Bailey, 1960). Approximately twenty million years ago, *Taxodium spp.* was wide spread across North America, Europe, and Asia, (Simpson, 1988; Tudge, 2006). *Taxodium spp.* have alternate, subulate to flat leaves (Bailey, 1960). Flowers are catkin-like, in terminal drooping panicles, and appear at the ends of branchlets from previous year's growth (Bailey, 1960). The fruit is a short-stalked globose cone composed of woody peltate scales, and the seeds are winged (Bailey, 1960). *Taxodium spp.* chromosome number is $2n=22$ (Sax and Sax, 1933; Stebbins, 1948). The exfoliating bark ranges in color from grey-brown to red-brown (Arnold, 2008).

Taxodium spp. are valued for their aesthetic value and contribution to the landscape in urban and riparian environments (Bailey and Bailey, 1976; Simpson, 1988). In addition to their ornamental value, *Taxodium spp.* are valuable timber trees (Bailey and Bailey, 1976) since the timber is light, strong, durable, straight grained, resistant to warping, slow to rot, and relatively easy to work (Petrides, 1972), and is used for boat and ship building, exterior trims, posts, poles, and rail road ties (Texas Forest Service, 1971). The seed of some species may be consumed by some wildlife (Petrides, 1972). Essential oils obtained from *Taxodium spp.* leaves and fruit have been reported to exhibit pronounced cytotoxic activites against human tumor cells (Ogunwande et al., 2007). Essential oils from fruit of *Taxodium spp.* is reported to have antifungal properties (Ogunwande et al., 2007).

Taxodium distichum (L.) L. Rich. (baldcypress) are majestic trees of considerable ornamental value (Bailey and Bailey, 1976). Its distribution ranges from Eastern North America to Mexico (Bailey and Bailey, 1976). It is a broad trunked, deciduous tree, occasionally reaching 45 m tall, with a dense spreading pendulous habit (Bailey, 1960; Bailey and Bailey, 1976). Young trees have a pyramidal shape, but will eventually form an irregular flattened canopy overtime. Bark on the trunk and larger branches is a light cinnamon-brown to red, which may become fibrous/finely divided by numerous longitudinal fissures over time (Bailey, 1960; Texas Forest Service, 1971). The base of the trunk may also become buttressed and deeply ridged over time (Petrides, 1972; Texas Forest Service, 1971). In addition, *T. distichum* may form projections (knees) from roots when grown under wet conditions (Bailey, 1960; Texas Forest Service, 1971; Petrides, 1972; Simpson, 1988). The projection's function is unclear; they were once thought to provide oxygen to the roots (Wells, 1942), although it is suggested that structural support and stabilization is more likely (DenUyl, 1961; Kramer et al., 1952). Leaves are small, 5-20 mm long, linear-lanceolate, arranged in two ranks (feather-like), acute, thin, and green to blue-green in color (Bailey, 1960), turning a rich brown in late autumn (Brickell, 2002). Cones are 1.5 to 4 cm in diameter, rugose with many thick shield shaped scales which disintegrate into irregular seeds (Bailey, 1960; Bailey and Bailey, 1976).

PLATANUS

The genus *Platanus* L. (Sycamore) belongs to the family Platanaceae Dumont. and includes approximately 7 species of deciduous or rarely partly evergreen trees, native to the Northern Hemisphere (Feng et al., 2005). The genus is wide spread in

America, Europe, and Southern Asia. The bark may obtain conspicuous coloration and texture overtime (Bailey, 1960). Leaves are broad, palmately lobed with palinactinodromous venation (Feng et al., 2005). Axillary buds are covered by the enlarged base of the leaf petiole (Feng et al., 2005). Inconspicuous terminal inflorescences appear in mid spring. A pendant, globose structure contains many 1-seeded nutlets in late winter (Bailey, 1960; Feng et al., 2005). *Platanus spp.* chromosome number is 2*n*=42 (Liu et al., 2007).

Platanus spp. are valued for their aesthetic value and contribution to the landscape in urban and rural environments (Liu et al., 2007). They are popular shade and avenue trees, which will withstand heavy pruning (Bailey and Bailey, 1976). The timber is heavy, hard, tough, course grained, and is considered to be difficult to work (Grimm, 1962; Petrides, 1972; Texas Forest Service, 1971). It is used for furniture, veneers, interior finishes, cabinetry, musical instruments, barrels, boxes, crates, and butcher blocks (Bailey and Bailey, 1976; Grimm, 1962; Petrides, 1972; Texas Forest Service, 1971). *Platanus spp.* has considerable potential as a bioenergy crop (Davis and Trettin, 2006; Dickmann, 2006; Ranney and Mann, 1994) *Platanus spp.* provide limited food and shelter for wildlife (Petrides, 1972). Prolonged contact with the fine hairs/down on stems, leaves, and fruit may irritate the skin and respiratory system (Brickell, 2002).

Platanus occidentalis L. (sycamore, American plane tree) are fast growing, lofty, majestic trees of considerable beauty (Bailey, 1960; Bailey and Bailey 1976). Its distribution ranges from Central North America and North Mexico to Canada (Bailey and Bailey, 1976). It is a deciduous tree that reaches heights of 45 m, with a broad open crown and attractive bark (Bailey and Bailey, 1976). Bark on young trunks and branches is smooth, creamy-white/yellow, which darkens overtime to a greenish-gray, which in turn exfoliates (flakes off in jigsaw-puzzle-like pieces) to reveal the nearly white/yellow younger bark beneath, adding considerable aesthetic interest (Texas Forest Service, 1971; Petrides, 1972). On mature specimens, the bark thickens and darkens to a deep furrowed brown. Leaves are large (4-10 in. across), glabrous, and shallowly lobed (3-5). Lobes are broader than long with sharply sinuate-dentate margins and cordate to truncate bases (Bailey, 1960; Bailey and Bailey, 1976). Flowers are visually insignificant, borne in spring in small globose heads (Petrides, 1972; Texas Forest Service, 1971). Fruit is multiple, small, hairy, solitary, and forms a small hanging brown ball (diameter of approximately 2.5 cm) on a flexible peduncle (Petrides, 1972; Texas Forest Service, 1971).

ULMUS

The genus *Ulmus* L. (Elm) belongs to the family Ulmaceae Mirb. and includes approximately 18 species of deciduous or rarely partly evergreen trees, native to the Northern Hemisphere (Corchete et al., 1997). The genus is wide spread in North America, Europe, Central Asia, and China. *Ulmus spp*. have alternate, simple leaves with toothed margins and usually an asymmetical base (Bailey and Bailey, 1976). The flowers are inconspicuous, bisexual, and appear before the leaves on most species (Corchete et al., 1997). The fruit is a winged samara with a notch at the apex (Tulin et al., 1964). *Ulmus spp.* chromosome number is 2n=28, except *Ulmus americana* L. which is 2n=4x=56 (Darlington and Wylie, 1956; Karnosky and Mickler, 1986). The bark is variable among species ranging from deeply ridged and furrowed to shallowly fissured to smooth, platy to exfoliating, and light gray to red-brown in color (Arnold, 2008).

Ulmus spp. are popular shade and avenue trees (Bailey and Bailey, 1976). They are historically valued for their aesthetic value and contribution to the landscape in urban and rural environments. *Ulmus spp*. make up one of the hardier groups of trees for harsh urban sites (Townsend, 1982). *Ulmus spp*. are also used as fence posts, in furniture, flooring, and boat building since the timber is resistant to splitting, decay, and water damage (Corchete et al., 1997). The sap of some species may be extracted for a variety of medicinal uses, including prevention and/or cure of fever (Campell-Culver, 2006).

Many *Ulmus spp*. were devasated by Dutch elm disease (DED), which is caused by the fungus *Ophiostoma ulmi* (Buisman) Nannf. and *O. novo-ulmi* Brasier (Brasier**,** 1990, 1991) and spread by elm bark beetles of the genus *Scolytus* Geoffrey. The effect of aggressive strains of DED has caused immense catastrophic damage to *Ulmus spp*. in

Europe and America and is responsible for the present severe DED pandemic (Corchete et al., 1997). Control of DED has been the object of numerous international research programs which have reported that sanitation methods, systemic fungicides, induced resistance, and resistant plants can be effective in the control of DED (Heybroek, 1992). Corchete et al. (1997) reports that the most promising approach for sustaining *Ulmus spp*. is selection and development of resistant individuals adapted to specific environmental conditions.

Ulmus parvifolia Jacq. (lacebark elm) has aesthetic value and is resistant to DED (Arnold, 2008). It is a partly evergreen tree in mild climates, 9 to 15 m high, with an open crown (Bailey and Bailey, 1976). *Ulmus parvifolia* is fast growing with long, arching, and somewhat weeping branches covered in 5 to 8 cm long dark green, leathery leaves (Gilman and Watson, 1994). Bark on the trunk exfoliates to reveal patterns of mottled grey, green, orange, and brown adding textural interest (Gilman and Watson, 1994).

Rational

In spite of all the research that already has been conducted on the effects of soil and environmental parameters such as soil type, soil bulk density, soil water content and soil temperature on above and belowground tree performance, comparatively little is known about the interactions between these parameters and transplanting practices. In the following chapters we explore the effect of planting depth on tree growth, development, and landscape establishment/survival under different cultural practices, including soil amendment, container production, irrigation, and season. In chapters II and III we studied the effect of planting depth and soil amendment on live oak and baldcypress, respectively. In chapter IV we explored the effect of planting depth during container production and subsequent landscape establishment of lacebark elm. In chapter V we examined the effect of planting depth and irrigation practices on growth and landscape establishment of sycamore. In chapter VI we looked at the effect of planting depth and transplant season on growth and landscape establishment of baldcypress.

CHAPTER II
EFFECT OF PLANTING DEPTH AND SOIL AMENDMENTS ON GROWTH AND PHYSIOLOGY OF LIVE OAK.

Introduction

Soil conditions are of particular importance for tree transplanting success in urban environments. Important soil conditions to consider during transplanting include soil pH, texture, and organic matter composition and/or location of soil nutrient pools (Consolly, 2007) as these factors may interact to affect soil structure, water-holding capacity, aeration, drainage, nutrient availability or toxicity, and root penetration and growth (Schenk and Jackson, 2002). A common practice to improve existing soil conditions at planting/transplanting is incorporation of organic or inorganic amendments to improve the physical, chemical, or biological properties of the soil (Bunt, 1988; Harris and Bassuk, 1993; Scheiber et al., 2007) including water use efficiency and availability (Pausas et al., 2004). However, these soil amendments may vary widely in their composition and effectiveness, depending on type, source or location (Bunt, 1988; Consolly, 2007; Scheiber et al., 2007).

Furthermore, variability in planting depth, specifically the location of the root collar relative to soil grade, may affect plant responses to soil conditions and/or amendments, due to physical/chemical impedance of root growth, nutrient deficiency or toxicity, and/or pest and disease exposure. In addition, optimum planting depth may vary among species, and may be dependent on cultural practices and/or environmental conditions (Arnold et al., 2005; Ball, 1999; Browne and Tilt, 1992; Drilias et al., 1982; Gilman and Grabosky, 2004; Pirone et al., 1988). This research was conducted to determine the interactions of different planting depths and soil amendments on growth and physiology of *Quercus virginiana* Mill., a common ornamental tree in urban environments, when planted in landscape trial beds. The null hypothesis was that planting depth would not affect growth or physiology of *Q. virginiana* when planted in different soil amendments.

Materials and Methods

CULTURAL CONDITIONS

This study was conducted under field conditions in three landscape trial beds (approximately 3.7 m x 11.7 m) at Texas A&M University Horticultural Gardens, College Station, Texas (lat. 30°37.78'N long. 96°20.51'W). Each landscape trial bed (block) was randomly split into four sections (approximately 3.7 m x 3.0 m) and amended as follows: control [sandy loam = native soil (Zack Series, Zack-urban land complex, fine, montmorillonitic, thermic, Udic Paleustalfs)], blasting sand incorporated 30% by volume, composted peat incorporated 30% by volume, or a sandy topsoil in raised bed at approximately 20 cm height.

Commercially grown (Greenleaf Nursery Co., El Campo, TX) *Quercus virginiana* (live oak) with an average height of 220.7±1.8 cm and average trunk diameter of 22.5±0.2 mm (at 15.2 cm above root flare) in 14.6-L (#5) black plastic containers (2000C Classic, Nursery Supplies, Inc., Chambersburg, PA) were purchased and transplanted into the landscape trial beds at 3 planting depths in relation to root collar (grade, 7.6 cm above grade, and 7.6 cm below grade) and drip irrigated (T-Tape®, T-Systems Intl. Inc., San Diego, CA) as required. Irrigation for each block/section was controlled separately and soil water potential was monitored (Model 2725, JetFill Tensiometers, Soil Moisture Equipment Corp., Santa Barbara, CA).

SOIL ASSESSMENT

Soil amendments and non-amended native soil (control) samples were collected prior to incorporation of treatments into the landscape trial beds and analyzed. The control (non-amended, native soil) had a textural analysis of 64% sand, 18% silt, and 16% clay (sandy loam), contained 2.77% organic matter (OM), pH 7.8, electrical conductivity (EC) 0.341 $dS \cdot m^{-1}$, and had nutrient levels with the following $\mu g \cdot g^{-1}$: 21 N, 52 P, 183 K, 2652 Ca, 435 Mg, 39 S, 438 Na, 26.76 Fe, 2.41 Zn, 2.3 Mn, 0.82 Cu, and 0.62 B (Soil, Water, and Forage Testing Laboratory, Texas A&M University, College Station, TX). The blasting sand amendment had a textural analysis of 96% sand, 2% silt, and 2% clay (sand), contained 0.18% OM, pH 8.7, EC 0.048 dS·m^{-1}, and had nutrient levels with the following µg·g^{-1}: 2 N, 2 P, 20 K, 16176 Ca, 117 Mg, 19 S, 123 Na, 2.72 Fe, 0.05 Zn, 1.12 Mn, 0.02 Cu, and 0.02 B. The composted peat amendment contained 68.48% OM, pH 7.1, EC 0.149, and had nutrient levels with the following µg·g^{-1}: 2 N, 81 P, 303 K, 1638 Ca, 159 Mg, 17 S, 172 Na, 2.97 Fe, 4.25 Zn, 10.09 Mn, 0.95 Cu, and 0.56 B. The sandy topsoil amendment used in raised beds had a textural analysis of 96% sand, 2% silt, and 2% clay (sand), contained 0.12% OM, pH 7.3, EC 0.044 dS·m^{-1}, and had nutrient levels with the following µg·g^{-1}: 1 N, 3 P, 24 K, 235 Ca, 42 Mg, 7 S, 111 Na, 1.53 Fe, 0.06 Zn, 1.82 Mn, 0.03 Cu, and 0.05 B.

Bulk density (g·cm^{-3}) was calculated (Dane and Topp, 2002) at the start and end (9 months after transplant) of the experiment. This procedure was modified as follows, 2.22 cm x 10 cm deep soil cores (3 per section) (7/8 in. x 33 in. SST Soil Probe with Cross Handle, Arts MFG. & Supply, American Falls, ID) were collected and dried (Model 214330, Tru-Temp Oven, Hotpack Corporation, Philadelphia, PA) for 7 d at 70 °C, and then weighed (Model 1412, Sartorius Balances & Scales, Brinkman Instruments, Co., Westbury, NY).

ASSESSMENT OF PLANT GROWTH

Tree height, from soil line to apical tip, and trunk diameter (approximately 15 cm above soil/substrate line) were measured at the start and end of the experiment. Relative growth rates (RGR) were calculated according to Hoffmann and Porter (2002) for tree height and trunk diameter. Stem xylem water potential was measured in autumn, winter, and spring using a pressure chamber (Model 610, Pressure Chamber Instrument, Pressure Moisture System, PMS Instrument Co., Corvallis, OR). Net photosynthetic activity was also determined at this time with a portable photosynthesis system (LI6400, LI-COR, Lincoln, NE), with red/blue LED light source (LI6400-02B) at photosynthetically active radiation (*PAR*) levels of 600 µmol·m^{-2}·s^{-1}, and CO_2 concentration of 360 µmol^{-1} from fully turgid, expanded, uniform, semi-mature leaves. Leaf temperature inside the leaf cuvette (2 cm^2 leaf area) was maintained at 25 °C.

Visual analysis of trees (shoot and root) was conducted at the end of the experiment. The shoot rating scale was as follows: 5 (green, healthy leaves uniformly distributed on tree), 4 (leaves uniformly distributed, but chlorotic), 3 (≤25% of leaves senesced), 2 (>25% of leaves senesced, but plant is still alive), and 1 (dead). Root rating scale was as follows: 5 (extensive thick, healthy root mass, lots of branching, and fibrous root growth), 4 (thicker, healthy root mass, branching, and fibrous root growth), 3 (some branching of root mass and fibrous root growth), 2 (girdling - roots still within original root ball), and 1 (dead).

Leaf chlorophyll concentration was determined at the end of the experiment, by extraction of chlorophyll with acetone (Harborne, 1973). This procedure was modified as follows, ten leaf discs (0.19 cm^2) per tree were collected from representative semi-mature leaves, placed in 5 mL of 80% acetone (Mallinckrodt Lab. Chemicals, Phillipsburg, NJ), and stored in the dark for 7 d at 4 °C. Supernatant was quantified with a spectrophotometer (Beckman Coulter™ Du® Series 640 UV/Vis Spectrophotometer, Beckman Coulter, Inc. Fullertan, CA) at 645 and 663 nm, and compared to an 80% acetone blank standard. Total chlorophyll concentration was expressed as $\mu g \cdot cm^{-2}$.

FUNGAL AND BACTERIAL POPULATIONS

Fungal and bacterial populations were estimated through preparation of decimal dilution series of soil samples (Alexander, 2005). This procedure was modified as follows: soil samples were collected from the rhizosphere of trees at the end of the experiment. Six cores per landscape trial bed section (one per tree) were collected and pooled. Samples were incubated in an oven set at 26 °C (Stabil-Therm®, Dry Type Bacteriological Incubator, Blue M Electric Co., Blue Island, IL) for approximately 4 d. Number of colonies were recorded and results were expressed as colony forming units per dry gram of soil sample ($cfu \cdot g^{-1}$).

STATISTICAL DESIGN

The experiment was a split plot design with four amendments [native soil (control), incorporated composted peat, incorporated sand, and sandy topsoil in a raised bed] as the main factor and three planting depths (root collars placed 7.6 cm above soil grade, at soil grade, and 7.6 cm below soil grade) as the subfactors with two replications per factorial per block (3 blocks). Data was analyzed using Analysis of Variance (ANOVA) or Restricted Maximum Likelihood (REML) in the JMP system for Windows, Release 7.02 (SAS Institute Inc., Cary, NC). The shoot and root quality ratings were analyzed using the Chi-Square option in the FREQ Procedure test in the SAS system for Windows, Release 9.1 (SAS Institute, Inc.).

Results

SOIL ASSESSMENT

Soil amendment did not have a significant ($P \leq 0.05$) effect on bulk density at the start of the experiment after amendments were tilled into the plots, but it did have a significant ($P = 0.005$) effect at the termination of the experiment (9 months) after settling (Table 2.1). In general, the sections with incorporated peat had significantly lower bulk densities compared to sections with incorporated sand or with sand in raised beds.

ASSESSMENT OF PLANT GROWTH

Planting the root collar 7.6 cm above soil grade resulted in 33% mortality, while planting at grade or planting 7.6 cm below grade resulted in 0% mortality. Soil amendment and planting depth did not significantly affect RGR_{height} from August 2005 to May 2007, and there was no significant amendment x planting depth interaction (Table 2.2). Soil amendment did not significantly affect $RGR_{diameter}$, and there was no significant amendment x planting depth interaction. However, planting depth significantly ($P = 0.016$) affected $RGR_{diameter}$. Trees planted 7.6 cm below grade had reduced (62%) $RGR_{diameter}$ when compared to trees planted at soil grade (Table 2.3).

Final height and trunk diameter were not significantly (P>0.05) affected by amendment and planting depth (data not shown).

Table 2.1. Effect of soil amendment on bulk density of soil at beginning and at termination of experiment.

Amendment[z]	Initial bulk density ($g \cdot cm^{-2}$)	Final bulk density ($g \cdot cm^{-2}$)
Control	1.43±0.04[y]	1.41±0.04
Incorporated sand	1.49±0.07	1.57±0.03
Incorporated peat	1.28±0.07	1.37±0.04
Raised sand	1.54±0.07	1.57±0.07
Significance[x]		
Amendment	0.055	0.005

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[y]Means ± standard error (n = 3).

[x]Significance according to ANOVA. P-values presented.

Table 2.2. Fixed effects test significance on relative growth rate (RGR) of height and diameter of live oak (*Quercus virginiana* Mill.) using the restricted maximum likelihood (REML) method.

Fixed effects test	RGR_{height}[z]	$RGR_{diameter}$[y]
Depth[x]	0.105[w]	0.016
Amendment[v]	0.318	0.110
Amendment x Depth	0.793	0.655

[z]Relative Growth Rate (RGR) calculated according to Hoffmann and Porter (2002). Height measured from soil line to apex of tree.

[y]Trunk diameter measured 15 cm above soil/substrate line.

[x]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).

[w]P-values.

[v]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

Date of measurement significantly ($P \leq 0.001$) affected mid-day stem water potential (Table 2.4). There was no significant planting depth or soil amendment main effect. There were no significant interactions for mid-day stem water potential. Trees had significantly more negative water potentials on the 15 October 2004 when compared to the 9 March and 26 May 2005 (Table 2.5). Date of measurement did not significantly affect pre-dawn stem water potential (Table 2.4).

Table 2.3. Effect of soil amendment and planting depth on relative growth rate (RGR) in height and diameter of live oak (*Quercus virginiana* Mill.) from August 2004 to May 2005.

Planting depth[z]	$RGR_{diameter}$[y] ($\mu m \cdot mm \cdot day^{-1}$)
Above	0.39±0.08[x]
Grade	0.46±0.07
Below	0.17±0.05

[z]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).
[y]Relative Growth Rate (RGR) calculated according to Hoffmann and Porter (2002). Trunk diameter measured 15 cm above soil/substrate line.
[x]Means±standard error (n=6).

Table 2.4. Fixed effects test significance on stem water potential (mid-day and pre-dawn) of live oak (*Quercus virginiana* Mill.) using the restricted maximum likelihood (REML) method.

Fixed effects test	Stem water potential (mid-day)	Stem water potential (pre-dawn)
Depth[z]	0.660[y]	0.587
Amendment[x]	0.282	0.402
Amendment x Depth	0.317	0.938
Date[w]	<0.001	0.717
Date x Amendment	0.094	0.653
Date x Depth	0.854	0.587
Date x Amendment x Depth	0.682	0.724

[z]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).
[y]*P*-values.
[x]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).
[w]Dates that stem water potential were measured were: 15 October 2004 (noon), 16 October 2004 (pre-dawn), 9 March 2005 (noon), 10 March 2005 (pre-dawn), 26 May 2005 (noon), 27 May 2005 (pre-dawn).

There was no significant planting depth or soil amendment main effect on pre-dawn stem water potential, and there were no significant interactions. Date of measurement significantly ($P \leq 0.001$) affected net photosynthetic activity (Table 2.6). There was no significant planting depth or soil amendment main effect on net photosynthetic activity, and there were no significant interactions. Net photosynthetic activity was significantly greater in May 2005 compared to March 2005 and intermediate in October 2004 (Table 2.7).

Table 2.5. Effect of date of measurement on mid-day stem water potential (Ψ) of live oak (*Quercus virginiana* Mill.).

Date	Ψ MPa
15 October 2004	-1.84±0.09[z]
9 March 2005	-1.10±0.08
26 May 2005	-0.96±0.06

[z]Means±standard error (n=3).

Table 2.6. Fixed effects test significance on net photosynthetic activity in live oak (*Quercus virginiana* Mill.) using the restricted maximum likelihood (REML) method.

Fixed effects test	Net photosynthetic activity
Depth[z]	0.236[y]
Amendment[x]	0.427
Amendment x Depth	0.985
Date[w]	<0.001
Date x Amendment	0.385
Date x Depth	0.940
Date x Amendment x Depth	0.991

[z]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).
[y]*P*-values.
[x]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand), incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).
[w]Dates that net photosynthetic activity was measured were: October 2004, March 2005, May 2005.

Table 2.7. Effect of date of measurement on net photosynthetic activity of live oak (*Quercus virginiana* Mill.).

Date	Net photosynthetic activity (μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$)
October 2004	7.5±0.6^z
March 2005	3.1±0.4
May 2005	13.9±1.3

^{z}Means±standard error (n=6).

There was a significant (Chi-square, P = 0.023) planting depth effect on shoot quality in the sand in raised bed sections (Fig. 2.1). In the sand in raised bed sections, at grade and above grade trees had more highly rated canopies than trees planted below grade (Fig. 2.1D). Planting depths in the other treatments did not have a significant ($P \leq$ 0.05) effect on shoot visual quality. However, trees grown in the incorporated sand section had nearly all of the trees, regardless of planting depth, rated at 5, while the trees in control sections and trees in incorporated peat sections had more trees rated as ≤ 4 (Fig. 2.1). There was a significant (Chi-square, P = 0.024) planting depth effect on root quality in the control sections (Fig. 2.2A). Planting depths in the other treatments did not have a significant ($P \leq 0.05$) effect on root visual quality. More trees in control plots had root systems rated poorly (1 or 2) than the other treatments (Fig. 2.2). For surviving trees in control plots root quality ratings were greater for trees planted above grade than at or below grade, however half of those planted above grade did not survive (Fig. 2.2A). Planting depth and soil amendment did not significantly affect total leaf chlorophyll concentration, and there was no significant amendment x planting depth interaction (Table 2.8).

FUNGAL AND BACTERIAL POPULATIONS

Soil amendment significantly ($P \leq 0.001$, P=0.037) affected soil fungal and bacterial colony forming units ($cfu \cdot g^{-1}$), respectively (Table 2.9). Sections with sand in raised beds and incorporated peat had less soil fungal colony forming units per dry gram of soil compared to control and incorporated sand sections. Control sections had

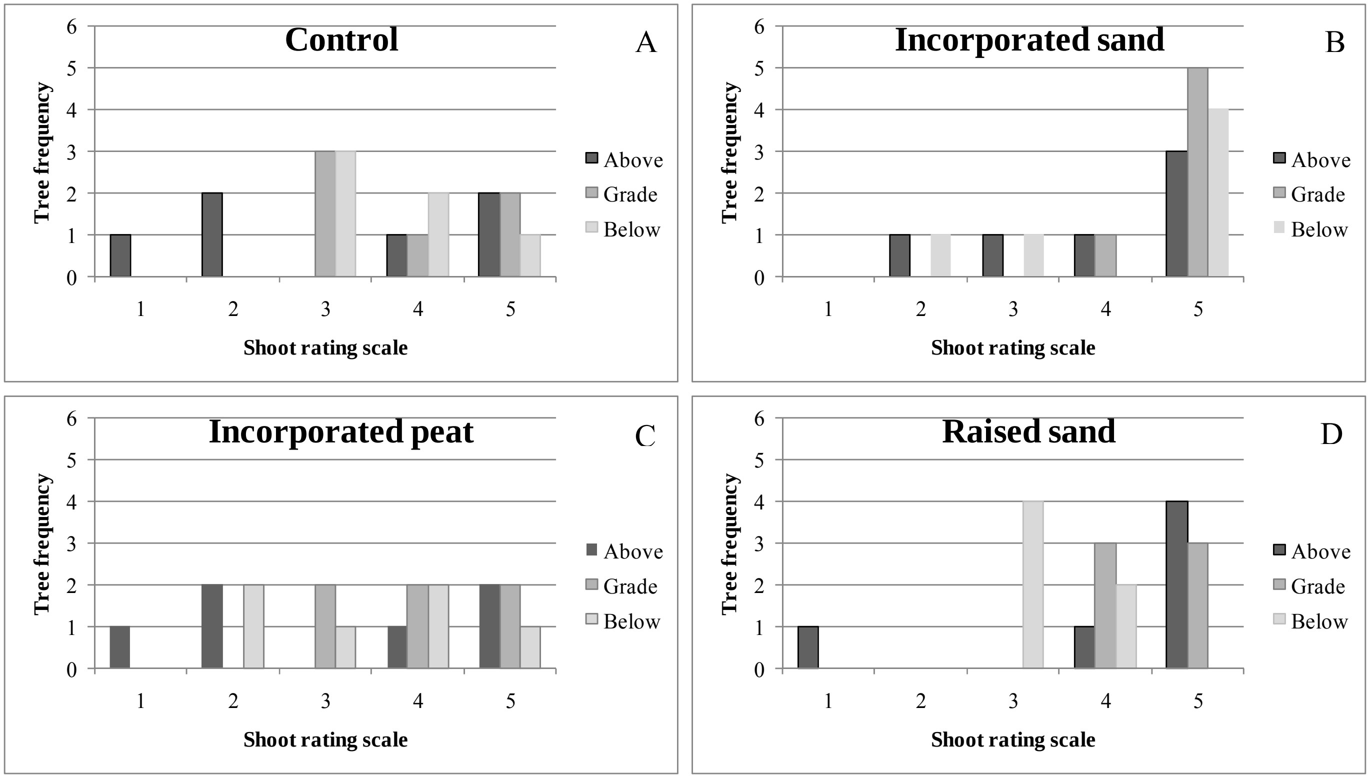

Fig. 2.1. Effect of soil amendment and planting depth on visual shoot quality ratings of live oak (*Quercus virginiana* Mill.). Soil amendments were one of the following: a native soil sandy loam (control) (A), incorporated (30% by volume) sand (incorporated sand) (B), incorporated (30% by volume) composted peat (incorporated peat) (C), or sand in a raised bed at 20 cm height (raised sand) (D). Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below). Shoot rating scale was as follows: 5 (green, healthy leaves uniformly distributed on tree), 4 (leaves uniformly distributed, but chlorotic), 3 (≤25% of leaves senesced), 2 (>25% of leaves senesced, but plant is still alive), and 1 (dead). Significant (Chi-square, P = 0.023) planting depth effect was found in sand in raised bed sections. Other amendments did not have a significant ($P \leq 0.05$) effect on shoot visual quality. Frequency (n = 6).

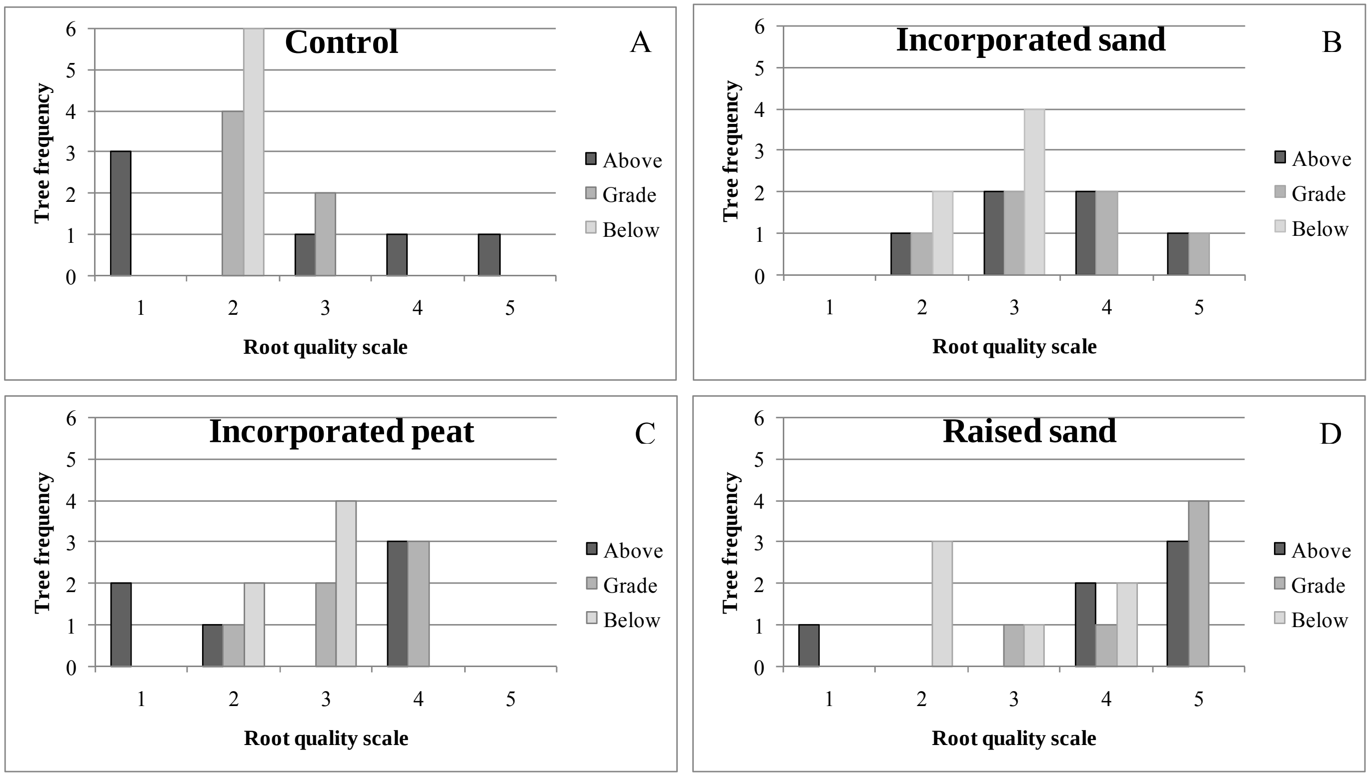

Fig. 2.2. Effect of soil amendment and planting depth on visual root quality ratings of live oak (*Quercus virginiana* Mill.). Soil amendments were one of the following: a native soil sandy loam (control) (A), incorporated (30% by volume) sand (incorporated sand) (B), incorporated (30% by volume) composted peat (incorporated peat) (C), or a sandy topsoil in a raised bed at 20 cm height (raised sand) (D). Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below). Root rating scale was as follows; 5 (extensive thick, healthy root mass, lots of branching, and fibrous root growth), 4 (thicker, healthy root mass, branching, and fibrous root growth), 3 (some branching of root mass and fibrous root growth), 2 (girdling - roots still within original root ball), and 1 (dead or dying). Significant (Chi-square, $P = 0.024$) planting depth effect was present in the control section. Planting depths were not significant ($P \leq 0.05$) with other amendments. Frequency ($n = 6$).

Table 2.8. Fixed effects test significance on soil amendment and planting depth on total leaf chlorophyll concentration of live oak (*Quercus virginiana* Mill.) using the restricted maximum likelihood (REML) method.

Fixed effects test	Total leaf chlorophyll concentration
Depth[z]	0.496[y]
Amendment[x]	0.185
Amendment x Depth	0.836

[z]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).
[y]*P*-values.
[x]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

Table 2.9. Effect of soil amendment on soil fungal and bacterial colony forming units per dry gram of soil sample ($cfu{\cdot}g^{-1}$).

Amendment[z]	Fungal ($cfu{\cdot}g^{-1}$)	Bacterial ($cfu{\cdot}g^{-1}$)
Control	56.9±5.5[y]	20.0±4.1
Incorporated sand	54.0±4.6	41.9±8.1
Incorporated peat	34.8±4.8	34.7±2.6
Raised sand	29.3±2.5	30.6±3.1
Significance[x]		
Amendment	<0.001	0.037

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).
[y]Means ± standard error (n=3).
[x]Significance according to ANOVA. *P*-values presented.

significantly less soil bacterial colony forming units per dry gram of soil than sections with incorporated sand.

Discussion

Soil amendment and planting depth affected root and shoot visual rating, and planting depth also affected $RGR_{diameter}$. Trees planted in the sand in raised bed sections had greater root visual ratings when compared to trees in the control sections. The control section was a sandy loam and thus had a higher water holding capacity (standing water was present after rainfall events) than the sand in raised bed sections. This could explain the high number of fungal colony forming units in the control section, although the fungal species were not characterized. Alternatively, the amendments in their physical handling and composition may contain few microbes (be inert). In addition, live oaks are susceptible to occasional root rots in wet soils (Arnold, 2008), although root rot was not observed in this study. The amount of air space in a substrate after free water has drained out is important as proper root growth and function is dependent on oxygen (Mathers et al., 2007). Irrigation or rainfall events may displace oxygen from soil pores, which in turn may limit root growth (Pokorny, 1987). Pirone (1972) reported that the roots of some species of oak (*Quercus* L.) are readily damaged as a result of low soil oxygen. Furthermore, Goss et al. (1990) and Armstrong and Drew (2002) reported that if oxygen partial pressure decreases below a certain level in the soil, as one would expect with increasing depth and/or reduced pore size, root growth and function could be impaired by anoxic conditions. Under these conditions the mobility of certain nutrients increases, specifically Fe and Mn, to potentially toxic levels, depending on the plant species. This may explain why trees planted 7.6 cm below grade had reduced root visual ratings when compared to trees planted at soil grade, although plant nutrient status in this study was not tested. Switzer (1960) also reported that survival of deeply planted loblolly pine (*Pinus taeda* L.) seedlings depended on soil conditions. In well drained soils, survival was greater than in poorly drained soils, but survival was similar across soil types when seedlings were planted at grade (Switzer, 1960).

Trees planted 7.6 cm below grade had reduced $RGR_{diameter}$ when compared to trees planted at soil grade. Arnold et al. (2007) reported that container-grown green ash (*Fraxinus pennsylvanica* Marsh.), sycamore (*Platanus occidentalis* L.), crapemyrtle (*Lagerstroemia indica* L. x *Lagerstroemia fauriei* Koehne. ‘Basham’s Party Pink’), oleander (*Nerium oleander* L. ‘Cranberry Cooler’) and vitex (*Vitex agnus-castus* L. ‘LeCompte’) transplanted into field soil (Boonville fine sandy loam) with the root collars 7.6 cm below grade were adversely affected with growth and survival severity varying among species. Planting root collars 7.6 cm below grade reduced height and trunk diameter in crapemyrtle, green ash, oleander, and vitex when compared to planting at or above grade (Arnold et al., 2007). A mortality rate of 33% (crapemyrtle), 50% (green ash), 33% (oleander), 50% (sycamore) and 0% (vitex) was reported 3 years after transplanting with root collars 7.6 cm below grade (Arnold et al., 2007). In contrast, trees in the present study planted 7.6 cm above grade had increased mortality compared to trees planted at grade or 7.6 cm below grade, because the container produced trees were top-heavy (high canopy to root ratio), and when planted above grade, trees were susceptible to wind blow over. Sparks (2005) reported a similar phenomenon where field grown pecan [*Carya illinoinensis* (Wangenh.) K. Koch] trees (3-year-old orchard) with graft unions set at 6 cm to 18 cm below grade had problems with trunk tilt, and trees set with graft union at 20 to 34 cm below grade blew over as a result of high winds (maximum sustained 54 to 70 $km \cdot hr^{-1}$).

Conclusion

Overall, tree growth was variable with trends from this preliminary research indicating that live oak trees under these study conditions had better growth when planted at grade in sand in raised beds as indicated by $RGR_{diameter}$ and root and shoot visual ratings. This preliminary study provided insight for a future study including using plant material propagated on site to ensure a known location of the original root collar and extending the duration of the study.

CHAPTER III
EFFECT OF SOIL AMENDMENTS AND PLANTING DEPTH ON GROWTH AND PHYSIOLOGY OF BALDCYPRESS

Introduction

Soil conditions are of particular importance for tree transplanting success in urban environments. Important soil conditions to consider during planting/transplanting include soil pH, texture, and organic matter composition and/or location of soil nutrient pools (Consolly, 2007). As these factors may interact to affect, soil structure, water-holding capacity, aeration, drainage, nutrient availability or toxicity, and thus root penetration and growth (Schenk and Jackson, 2002). Some species are readily damaged as a result of low soil oxygen (Pirone, 1972). The extent of damage to roots as a result of low soil oxygen was suggested to be dependent on a number of interacting factors, including: plant species, soil bulk density, total pore space, water retention and air-filled porosity, and duration of low oxygen event (Kozlowski and Davies, 1975; Pirone, 1972). A common practice to improve existing soil conditions at transplanting is incorporation of organic and/or inorganic amendments to improve the physical, chemical, and biological properties of the soil (Bunt, 1988; Harris and Bassuk, 1993; Scheiber et al., 2007) including water use efficiency and availability (Pausas et al., 2004). However, these soil amendments may vary widely in their composition and effectiveness (Bunt, 1988; Consolly, 2007; Scheiber et al., 2007).

At transplanting and during landscape establishment, trees are prone to water deficits as a result of decreased root growth and development, which result in decreased ability for roots to absorb soil moisture (Haase and Rose, 1993; Rietveld, 1989). Furthermore, variability in planting depth, specifically the location of the root collar relative to soil grade, may affect plant response to soil conditions and/or amendments, due to physical impedance of root growth, nutrient deficiency or toxicity, and/or pest and disease exposure. In addition, optimum planting depth may vary among species, and may be dependent on cultural practices and/or environmental conditions (Arnold et al., 2005; Ball, 1999; Browne and Tilt, 1992; Drilias et al., 1982; Gilman and Grabosky, 2004; Pirone et al., 1988). Therefore this study was conducted to determine the interactions of different soil amendments and planting depths on growth and physiology of baldcypress (*Taxodium distichum* (L.) L. Rich.), a common landscape tree in urban and riparian environments (Bailey and Bailey, 1976; Simpson, 1988).

Materials and Methods

CULTURAL CONDITIONS

Taxodium distichum seeds were collected in San Marcos, Texas (lat. 29°52.730'N long. 97°55.962'W) and stored under ambient conditions until required. Seeds were immersed in a heated (approximately 43 °C) water bath (180 Series Water Bath, Precision Scientific Inc., Chicago, IL), left to soak for approximately 24 h in the cooling water (to approximately 23 °C), and were then rinsed in reverse osmosis treated (RO) water. Seeds were stratified in a cold room (1.7 °C; Bally Case and Cooler, Inc., Bally, PA) for 90 d in moist peat (Premier® Pro Moss® TBK Professional, Premier Horticulture Inc., Red Hill, PA) (Hartmann et al., 2002), and then planted in 10 cm x 36 cm x 51 cm black plastic flats (Dyna-flat™, Kadon Corp., Dayton, OH) containing vermiculite (Sunshine® Strong-Lite® Medium Vermiculite Premium Grade, SUN GRO™ Horticulture, Pine Bluff, AR), and placed in a greenhouse at the Texas A&M University Horticultural Gardens, College Station, TX (lat. 30°37.78'N long. 96°20.51'W). Emerging seedlings were irrigated with RO water as required.

Uniform seedlings (approximately 11 cm in height) were transplanted after approximately 100 d, into 0.85 L black plastic containers (Dillen Products, Middlefield, OH) with their root collars at substrate (Metro-Mix® 700 Series, SUNGRO®, Bellevue, WA) surface (grade). Transplanted seedlings were maintained under shade (55% light exclusion) in a graveled nursery at Texas A&M University Horticultural Gardens. Plants were fertigated (0.27 $L \cdot min^{-1}$ flow rate) as required with sulfuric acid injected water (pH 6.3-6.5) containing 50 $mg \cdot L^{-1}$ of N from a water soluble fertilizer (Peter

Professional® Acid Special water soluble fertilizer, 21N-3.1P-5.8K, Scott's Company, Marysville, OH).

Young trees (liners) were transplanted, after approximately 80 d, into 2.6 L (#1) black plastic containers (C-300S Classic, Nursery Supplies, Inc., Chambersburg, PA) with their root collars at substrate (composted pine bark mulch; Landscapers Pride®, New Waverly, TX) surface (grade). Container substrate was amended with the following, 7 $kg \cdot m^{-3}$ 15N-3.9P-9.9K controlled release fertilizer (Scotts Osmocote®Plus 15-9-12, Scotts-Sierra Horticultural Products Co., Marysville, OH), 4 $kg \cdot m^{-3}$ dolomitic limestone (Austin White Lime Company, Austin, TX), 2 $kg \cdot m^{-3}$ gypsum (Hoedown™ Standard Gypsum LP, Fredericksburg, TX), and 1 $kg \cdot m^{-3}$ micronutrients (Scotts Micromax® micronutrients, Scotts-Sierra Horticultural Products Co., Marysville, OH). Liners were maintained in the nursery under 55% shade and fertigated as previously described.

Trees were transplanted, after approximately 225 d, into 10.8 L (#3) black plastic containers (1200C Classic, Nursery Supplies, Inc., Chambersburg, PA) with their root collars at the substrate (composted pine bark mulch; Earth's Finest Black Diamond Mulch, The LetCo Group, Dallas, TX) surface (grade). Container substrate was amended as described previously. Trees were maintained in the nursery under shade and fertigated as previously described. Trees were staked (1.2 m bamboo stakes; Tonkin Bamboo Cane, Welli Tonkin Bamboo Export Co., Ltd., Shenzhen, China) and tied (Tapener® HT-B2 Max®, Max Co. Ltd., Tokyo, Japan) to maintain a central leader.

Trees (average height 68.2±0.9 cm and trunk diameter 8.6±0.1 mm) were transplanted, after approximately 50 d, into three landscape trial beds (approximately 3.7 m x 11.7 m) at the Texas A&M University Horticultural Gardens at three different planting depths in relation to the root collar, grade (root collar at soil surface), 7.6 cm above grade, or 7.6 cm below grade. Each of three landscape trial beds (blocks) was split into four sections. Each section was amended with one of the following: control [sandy loam native soil (Zack Series, Zack-urban land complex, fine, montmorillonitic, thermic, Udic Paleustalfs)], sand incorporated 30% by volume, composted peat incorporated 30%

by volume, or a sandy topsoil in a raised (~20 cm) bed. Trees were irrigated as required using soaker hoses (Swan® Soaker Hose, Colorite Plastics, Co., Ridgefield, NJ). Irrigation for each section was controlled separately and soil volumetric water content was monitored (Model EC-20, ECH_2O Probe, Decagon Devices, Inc., Pullman, WA) (1 probe per section) and logged (Em5, ECH_2O Logger, Decagon Devices, Inc., Pullman, WA) periodically throughout the study.

SOIL ASSESSMENT

Soil samples were collected for each section after incorporation of amendments at the beginning of the study and analyzed (Soil, Water, and Forage Testing Laboratory, Texas A&M University, College Station, TX). Bulk density ($g \cdot cm^{-3}$) was calculated (Dane and Topp, 2002) at the start and end (approximately 27 months after transplant) of the experiment. This procedure (Dane and Topp, 2002) was modified as follows, 2.22 cm x 10 cm deep soil cores (3 per section) (7/8 in. x 33 in. SST Soil Probe with Cross Handle, Arts MFG. & Supply, American Falls, ID) were collected and dried (Model 214330, Tru-Temp Oven, Hotpack Corporation, Philadelphia, PA) for 7 d at $70^{o}C$, and then weighed (Model 1412, Sartorius Balances & Scales, Brinkman Instruments, Co., Westbury, NY).

Soil oxygen content and soil temperature were measured in June and August 2007. For soil oxygen content measurements, chambers (CPVC, 1.2 cm inner diameter) were installed in each section at three depths: 7.5 cm, 15 cm, and 30 cm (n=3). The chambers were capped with septum stoppers (Red septum stopper No. 21, Fisherbrand, Loughborough, UK). Oxygen was extracted using a syringe. The volume of each chamber was extracted prior to collecting the amount used for analysis. The volume collected for analysis was then analyzed using a portable oxygen analyzer (Model 574, Portable O_2 Analyser, FPA with Pump, Servomex Co. Inc., Sugar Land, TX). Soil oxygen was expressed as a percent value. Soil temperature was collected at two soil depths: 7.5 cm and 15 cm using a data logger thermometer (Model HH309, Omega Engineering, Inc., Stamford, CT).

ASSESSMENT OF PLANT GROWTH

Tree height, from soil line to apical tip, and trunk diameter (15 cm above soil/substrate line) were measured approximately every 6 months. Stem xylem water potential was measured periodically in the summer, autumn, and spring using a pressure chamber (Model 610, Pressure Chamber Instrument, Pressure Moisture System, PMS Instrument Co., Corvallis, OR). Net photosynthetic activity was also determined at this time with a portable photosynthesis system (LI6400, LI-COR, Lincoln, NE), with red/blue LED light source (LI6400-02B) at photosynthetically active radiation (*PAR*) levels of 600 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and CO_2 concentration of 360 μmol^{-1} from fully turgid, expanded, uniform, semi-mature leaves. Leaf temperature inside the leaf cuvette (2 cm^2 leaf area) was maintained at 25 °C.

Physiologically mature leaves were collected at harvest (n = 3) and ground to pass a 40-mesh screen. Tissue analysis of N, P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu, Al, B, and Mo, was conducted (AgSource Harris Laboratory, Lincoln, NE).

Leaf chlorophyll concentration was determined at termination of the experiment, by extraction of chlorophyll with acetone (Harborne, 1973). This procedure was modified as follows, leaves were collected from representative semi-mature leaves and fresh mass was determined. Leaves were placed in 5 mL of 80% acetone (Mallinckrodt Lab. Chemicals, Phillipsburg, NJ) and stored in the dark for 7 d at 4 °C. Supernatant was quantified with a spectrophotometer (Beckman Coulter™ Du® Series 640 UV/Vis Spectrophotometer, Beckman Coulter, Inc. Fullertan, CA) at 646 and 663 nm, and compared to an 80% acetone blank standard. Total chlorophyll concentration was expressed as $mg \cdot g^{-1}$ of fresh mass.

Soil cores (5 cm x 20 cm) were extracted approximately 30 cm from each tree trunk using a soil core sampler (AMS stainless steel soil core sampler with hammer, AMS Inc., American Falls, ID) centered at 7.5 and 15 cm (±2.5 cm) depths. Soil cores were chilled (2 °C) until processed. Roots were sieved from the soil cores and then divided into two diameter classes: fine (average diameter < 1 mm) and coarse (average diameter ≥ 1 mm) roots. Roots were scanned (Epson Perfection V700 PHOTO, Epson

America, Inc., Long Beach, CA) and analyzed (WinRHIZO Pro 2007d, Regent Instruments, Inc. Nepean, ON, Canada) for total root length and average root diameter. Roots were then dried (Model 214330, Tru-Temp Oven, Hotpack Corp., Philadelphia, PA) for 7 d at 70 °C and weighed. Specific root length (SRL) was then calculated.

Shoot dry mass was determined at the end of the experiment. Shoots were harvested, dried (Model 214330, Tru-Temp Oven, Hotpack Corporation, Philadelphia, PA) for 7 d at 70 °C, and then weighed.

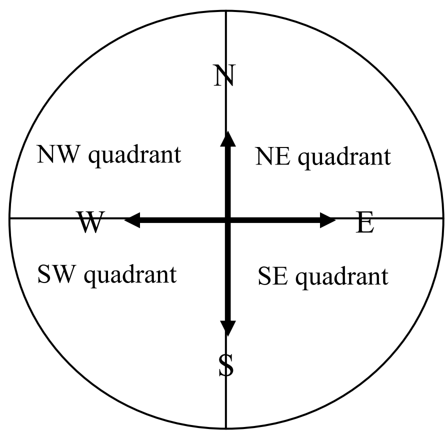

Fig. 3.1. Baldcypress (*Taxodium distichum* (L.) L. Rich.) root balls were visually divided into four quadrants in cardinal directions.

Coarse root analysis was conducted after shoot harvest. A trench was dug around each trunk approximately 30 cm from the base at a depth of approximately 15 cm. The root ball was visually divided into four quadrants in cardinal directions (Fig. 3.1) and roots ≥ 2 cm in diameter and 2 cm > x > 1 cm were counted and recorded. The root angle relative to the trunk was recorded on roots ≥ 2 cm in diameter and within the top 3 cm of the original root ball in order to determine the incidence of potential stem girdling roots.

STATISTICAL DESIGN

The experiment was a split plot design with four amendments [native soil (control), incorporated composted peat, incorporated sand, and sandy topsoil in a raised bed] as the main factor and three planting depths (root collars placed 7.6 cm above soil grade, at soil grade, and 7.6 cm below soil grade) as the subfactors with two replications per factorial per block (3 blocks). Data was analyzed using Analysis of Variance (ANOVA) in the SAS system for Windows, Release 8.1 (SAS Institute Inc., Cary, NC), or Restricted Maximum Likelihood (REML) in the JMP system for Windows, Release 7.02 (SAS Institute Inc.).

Results

SOIL ASSESSMENT

Soil amendments had no significant ($P \leq 0.05$) effect on N, P, K, Ca, Mg, S, Zn, Cu, pH, or EC (Tables 3.1 and 3.2). Soil amendments significantly (P = 0.044, 0.003, 0.001, and 0.013, respectively) affected soil Na, Fe, Mn concentrations and organic matter content (Tables 3.1 and 3.2). The sand in raised beds had significantly lower Na and Fe concentrations when compared to the other amendments and the control. The incorporated peat section had significantly greater Mn concentration and organic matter content when compared to the other treatments.

Soil amendment did not have a significant (P = 0.480) effect on bulk density of the tilled plots at the start of the experiment (Table 3.3), but it did have a significant ($P \leq$ 0.001) effect at the termination of the experiment (27 months) as the soil settled. In general the sections with incorporated peat and native soil (control) had lower bulk densities compared to sections with incorporated sand or with sand in raised beds.

Date of measurement, date x amendment, date x depth, and date x amendment x depth had a significant ($P \leq 0.001$) effect on soil oxygen content (Table 3.4). There was no significant chamber depth or amendment main effect. Oxygen content was lowest (12%) on 27 June 2007 and highest (19%) on 11 August 2007 across treatments (Fig. 3.2). In general, soil oxygen content decreased with increasing depth, apart from on the

Table 3.1. Soil macronutrient and Na concentration for native and amended soil sections.

Amendment[z]	N ($\mu g \cdot g^{-1}$)	P ($\mu g \cdot g^{-1}$)	K ($\mu g \cdot g^{-1}$)	Ca ($\mu g \cdot g^{-1}$)	Mg ($\mu g \cdot g^{-1}$)	S ($\mu g \cdot g^{-1}$)	Na ($\mu g \cdot g^{-1}$)
Control	16.7±8.2[y]	65.0±44.7	199.3±66.0	2470.7±1012.8	361.3±92.9	41.7±18.4	391.0±38.7
Incorporated sand	5.3±0.9	19.3±4.4	98.7±17.1	2657.3±368.3	222.7±52.1	19.7±3.5	314.0±60.1
Incorporated peat	5.3±1.7	67.3±11.7	215.3±26.0	2581.0±512.7	339.7±71.4	27.7±6.1	393.7±27.7
Raised sand	3.7±1.2	47.7±40.2	50.0±3.5	1297.7±724.2	123.3±11.8	13.7±3.7	196.7±4.2
Significance[w]							
Amendment	0.268	0.728	0.073	0.588	0.187	0.382	0.044

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[y]Means±standard error (n=3).

[w]Significance according to ANOVA. *P*-values presented.

Table 3.2. Soil micronutrient concentration, pH, electrical conductivity (EC), and organic matter (OM) content for native and amended soil sections.

Amendment[z]	Fe ($\mu g \cdot g^{-1}$)	Zn ($\mu g \cdot g^{-1}$)	Mn ($\mu g \cdot g^{-1}$)	Cu ($\mu g \cdot g^{-1}$)	pH	EC ($dS \cdot m^{-1}$)	OM (%)
Control	22.6±2.8[y]	2.2±1.2	2.2±0.2	0.9±0.5	7.8±0.2	0.3±0.1	2.1±0.8
Incorporated sand	16.9±2.8	1.0±0.3	2.2±0.4	0.5±0.0	8.3±0.2	0.3±0.1	1.4±0.4
Incorporated peat	25.4±1.3	3.4±0.9	4.7±0.1	1.1±0.2	7.7±0.3	0.2±0.0	6.3±1.2
Raised sand	5.8±1.7	1.1±0.8	1.7±0.1	0.5±0.3	7.9±0.2	0.1±0.0	0.7±0.5
Significance[x]							
Amendment	0.003	0.381	0.001	0.520	0.416	0.276	0.013

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[y]Means±standard error (n=3).

[x]Significance according to ANOVA. *P*-values.

Table 3.3. Effect of soil amendment on bulk density of soil at beginning and at termination of experiment.

Amendment[z]	Initial bulk density ($g \cdot cm^{-2}$)	Final bulk density ($g \cdot cm^{-2}$)
Control	1.5±0.1[y]	1.6±0.0
Incorporated sand	1.6±0.1	1.8±0.1
Incorporated peat	1.4±0.1	1.5±0.0
Raised sand	1.5±0.1	1.9±0.1
Significance[x]		
Amendment	0.480	<0.001

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[y]Means ± standard error (n=3).

[x]Significance according to ANOVA. *P*-values presented.

Table 3.4. Fixed effects test significance on soil oxygen content using the restricted maximum likelihood (REML) method.

Fixed effects test	Soil oxygen content
Depth[z]	0.123[y]
Amendment[x]	0.411
Amendment x Depth	0.465
Date[w]	<0.001
Date x Amendment	<0.001
Date x Depth	<0.001
Date x Amendment x Depth	<0.001

[z]Chambers (CPVC, 1.2 cm inner diameter) were installed in each amended section in the trial beds at one of three depths: 7.5 cm, 15 cm, or 30 cm.

[y]*P*-values.

[x]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[w]Dates that soil oxygen was measured were: 4-6 June 2007, 27 June 2007, 11 August 2007, 14-16 August 2007.

27 June 2007 where soil oxygen content was lowest at the shallow (7.5 cm) depth in the control, incorporated peat, and incorporated sand sections.

Date of measurement, date x amendment, and date x depth had a significant ($P \leq 0.001$) effect on soil temperature (Table 3.5). Soil amendment and depth of temperature sensor significantly (P = 0.002 and 0.038, respectively) affected soil temperature. There

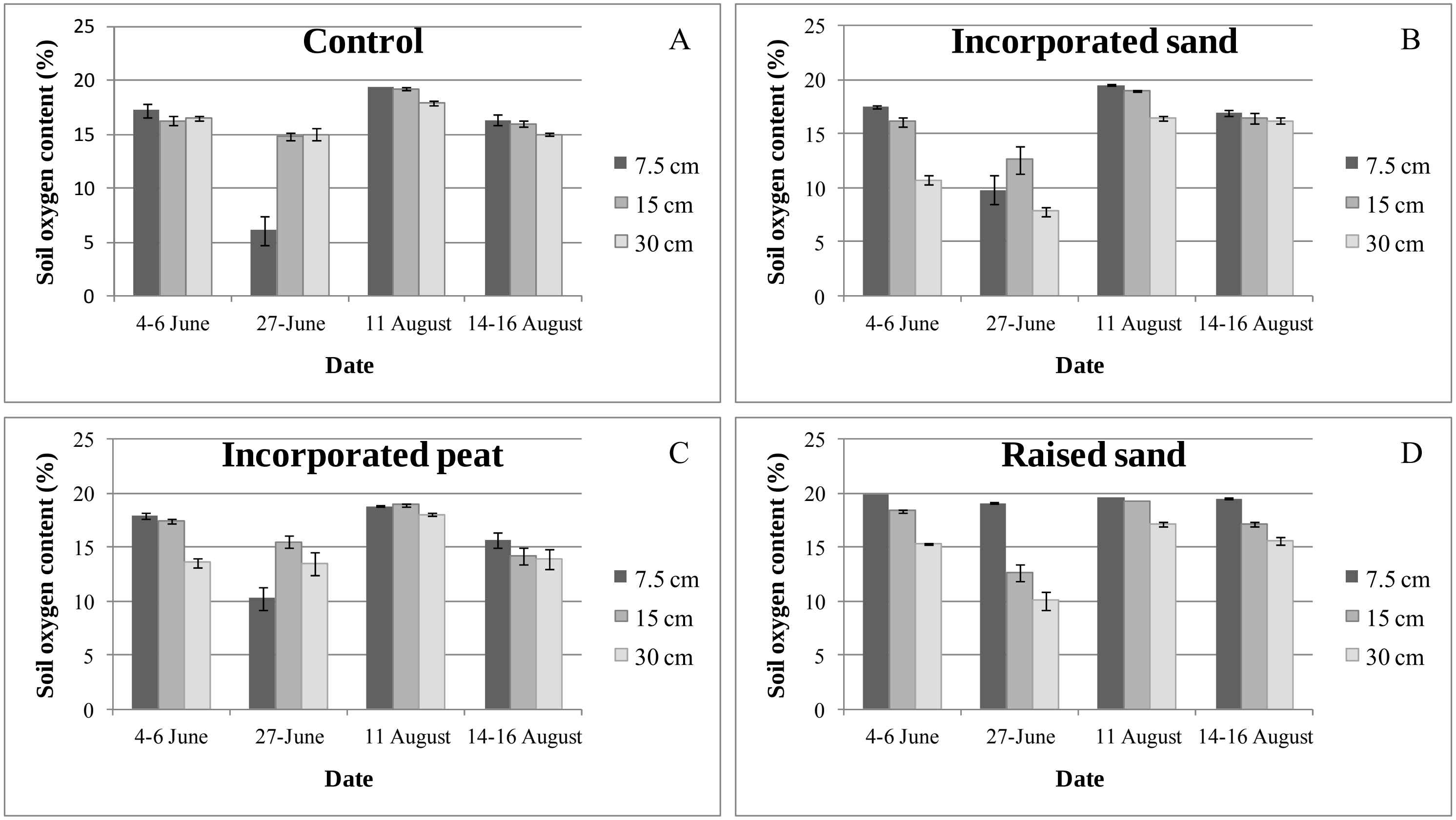

Fig. 3.2. Effect of soil amendment, chamber depth placement, and date on soil oxygen content in summer 2007. Means±standard error (n=3). Soil amendments were one of the following: a native soil sandy loam (control) (A), incorporated (30% by volume) sand (incorporated sand) (B), incorporated (30% by volume) composted peat (incorporated peat) (C), or a sandy topsoil in a raised bed at 20 cm height (raised sand) (D). Chambers (CPVC, 1.2 cm inner diameter) were installed in each amended section in the trial beds at one of three depths: 7.5 cm, 15 cm, or 30 cm.

Table 3.5. Fixed effects test significance on soil afternoon temperatures using the restricted maximum likelihood (REML) method.

Fixed effects test	Soil temperature
Depth[z]	0.038[y]
Amendment[x]	0.003
Amendment x Depth	0.987
Date[w]	<0.001
Date x Amendment	<0.001
Date x Depth	<0.001
Date x Amendment x Depth	0.732

[z]Temperature sensor was placed at a depth of either 7.5 or 15 cm

[y]*P*-values.

[x]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[w]Dates that soil temperature was measured were: 4-6 June 2007, 27 June 2007, 11 August 2007, 14-16 August 2007.

was no significant amendment x sensor depth interaction (Table 3.5). Soil temperature was lowest (27 °C) on 4-6 and 27 June 2007 and highest (31 °C) on 11 August 2007 (Table 3.6). The sand amendment in the raised bed sections had significantly higher (~ 2 °C) soil temperatures compared to the other soil treatments. Soil temperature measured at the 15 cm depth was significantly cooler (~1 °C) than soil temperature at 7.5 cm depth.

Date of measurement and date x amendment had a significant ($P \leq 0.001$) effect on soil moisture content (Table 3.7). The main effect of soil amendment was not significant (Table 3.7). Soil moisture content averaged across amendments was greatest on 27 June 2007 (0.40 $m^3 \cdot m^3$) and lowest on 11 August 2007 (0.22 $m^3 \cdot m^3$) (Table 3.8).

ASSESSMENT OF PLANT GROWTH

Date of measurement had a significant ($P \leq 0.001$) effect on relative growth rate in height (RGR_{height}) and diameter ($RGR_{diameter}$) (Table 3.9). The main effect of planting depth was significant (P=0.047) for RGR_{height}, but not $RGR_{diameter}$ The main effect of soil amendment was not significant for RGR_{height} or $RGR_{diameter}$.. There was a significant (P = 0.31, P < 0.001) date x depth interaction on relative growth rate in height (RGR_{height}) and

Table 3.6. Effect of soil amendment, soil temperature sensor depth, and date on soil temperature in summer 2007.

Factor		Soil Temperature (°C) 4-6 June 2007	27 June 2007	11 August 2007	14-16 August 2007
Amendment[z]	Control	26.7±0.2	26.7±0.1	30.2±0.2	28.7±0.3
	Incorporated sand	25.3±0.1	26.5±0.2	30.7±0.2	28.3±0.2
	Incorporated peat	26.1±0.1	26.3±0.1	29.6±0.2	28.5±0.2
	Raised sand	29.5±0.6	27.1±0.2	32.5±0.3	29.2±0.2
Sensor depth[x]	7.5 cm	27.4±0.3	26.9±0.1	31.4±0.2	28.8±0.2
	15 cm	26.4±0.2	26.4±0.1	30.1±0.2	28.6±0.1

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[y]Means ± standard error (n=3).

[x]Temperature sensor was placed at a depth of either 7.5 or 15 cm.

Table 3.7. Fixed effects test significance on soil moisture content using the restricted maximum likelihood (REML) method.

Fixed effects test	Soil moisture content
Amendment[z]	0.112[y]
Date[x]	<0.001
Date x Amendment	<0.001

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[y]*P*-values.

[x]Dates reported: 4-6 June 2007, 27 June 2007, 11 August 2007, and 14-16 August 2007.

Table 3.8. Effect of soil amendment on soil moisture content ($m^3 \cdot m^3$).

	Soil moisture content ($m^3 \cdot m^3$)			
Amendment[z]	4-6 June 2007	27 June 2007	11 August 2007	14-16 August 2007
Control	0.26±0.00[y]	0.39±0.01	0.17±0.00	0.27±0.01
Incorporated sand	0.43±0.02	0.48±0.02	0.31±0.02	0.29±0.00
Incorporated peat	0.23±0.01	0.39±0.00	0.18±0.01	0.23±0.01
Raised sand	0.26±0.00	0.33±0.00	0.23±0.00	0.28±0.00

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[y]Means ± standard error (n=3).

diameter ($RGR_{diameter}$). There was a significant date x amendment interaction in RGR_{height}. The greatest RGR_{height} occurred from December 2005 to June 2006 and from December 2006 to June 2007, and the lowest RGR_{height} occurred from June 2005 to December 2005 (Table 3.10). Trees planted 7.6 cm above grade had significantly lower RGR_{height} than trees planted at soil grade during three measurement periods. In general, trees in the incorporated sand and sand in raised beds sections had the greatest RGR_{height} initially while trees in control sections had the greatest RGR_{height} later in the experiment (Table 3.10). The greatest $RGR_{diameter}$ occurred from June 2005 to December 2005, and the lowest $RGR_{diameter}$ occurred from June 2007 to September 2007 (Table 3.11). In general, $RGR_{diameter}$ during the first 6 months was greatest for trees planted at grade. In spring 2006, $RGR_{diameter}$ was greatest for trees planted above soil grade, while the trend was reversed in spring 2007 with the trees planted below grade averaging greater $RGR_{diameter}$. Little differences in $RGR_{diameter}$ were found during late summer and autumn of 2006 or 2007. Final height and trunk diameter were not significantly ($P \leq 0.05$) affected by planting depth (data not shown). Final height was significantly ($P = 0.001$) affected by amendment (Fig. 3.3), but trunk diameter was not significantly affected by amendment (data not shown). There was no significant planting depth x amendment interaction for height and trunk diameter. Trees planted in control sections were significantly shorter at harvest compared to trees planted in other soil treatments.

Table 3.9. Fixed effects test significance on relative growth rate (RGR) of height and diameter of baldcypress (*Taxodium distichum* (L.) L. Rich.) using the restricted maximum likelihood (REML) method.

Fixed effects test	RGR_{height} [z]	$RGR_{diameter}$ [y]
Depth[x]	0.047[w]	0.174
Amendment[v]	0.195	0.226
Amendment x Depth	0.447	0.354
Date[u]	<0.001	<0.001
Date x Amendment	0.010	0.089
Date x Depth	0.031	<0.001
Date x Amendment x Depth	0.932	0.990

[z]Relative Growth Rate (RGR) calculated according to Hoffmann and Porter (2002). Height measured from soil line to apex of tree.

[y]Trunk diameter measured 15 cm above soil/substrate line.

[x]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).

[w]*P*-values.

[v]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[u]Dates that height and diameter were measured: June 2005, December 2005, June 2006, December 2006, June 2007, and September 2007.

Table 3.10. Effect of soil amendment and planting depth on relative growth rate in height (RGR_{height}) of baldcypress (*Taxodium distichum* (L.) L. Rich.).

Factor		$RGR_{height}{}^{z}$ (µm·mm·day^{-1})				
		June 2005-December 2005	December 2005-June 2006	June 2006-December 2006	December 2006-June 2007	June 2007-September 2007
Amendment[y]	Control	0.2±0.2[x]	2.2±0.2	1.1±0.1	2.4±0.1	1.8±0.2
	Incorporated sand	1.1±0.3	2.3±0.2	1.7±0.1	2.1±0.1	1.4±0.2
	Incorporated peat	0.7±0.3	2.6±0.2	1.2±0.2	2.0±0.1	1.5±0.2
	Raised sand	1.0±0.3	2.1±0.2	1.2±0.2	1.9±0.1	1.4±0.2
Planting depth[w]	Above	0.8±0.2	2.1±0.1	1.2±0.1	2.1±0.1	1.2±0.1
	Grade	1.2±0.2	2.3±0.1	1.2±0.1	2.0±0.1	1.7±0.1
	Below	0.4±0.2	2.4±0.2	1.4±0.2	2.2±0.1	1.7±0.1

[z]Relative Growth Rate (RGR) calculated according to Hoffmann and Porter (2002). Height measured from soil line to apex of tree.

[y]Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[x]Means±standard error (n=6).

[w]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).

Table 3.11. Effect of soil amendment and planting depth on relative growth rate in trunk diameter ($RGR_{diameter}$) of baldcypress (*Taxodium distichum* (L.) L. Rich.).

	$RGR_{diameter}{}^{z}$ (µm·mm·day^{-1})				
Planting depth[y]	June 2005-December 2005	December 2005-June 2006	June 2006-December 2006	December 2006-June 2007	June 2007-September 2007
Above	3.8±0.3[x]	3.2±0.1	1.8±0.1	1.7±0.1	1.5±0.2
Grade	5.0±0.3	2.7±0.1	1.8±0.1	1.9±0.1	1.2±0.1
Below	3.8±0.4	2.6±0.2	1.9±0.2	2.1±0.2	1.3±0.2

[z]Relative Growth Rate (RGR) calculated according to Hoffmann and Porter (2002). Trunk diameter measured 15 cm above soil/substrate line.

[y]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).

[x]Means±standard error (n=6).

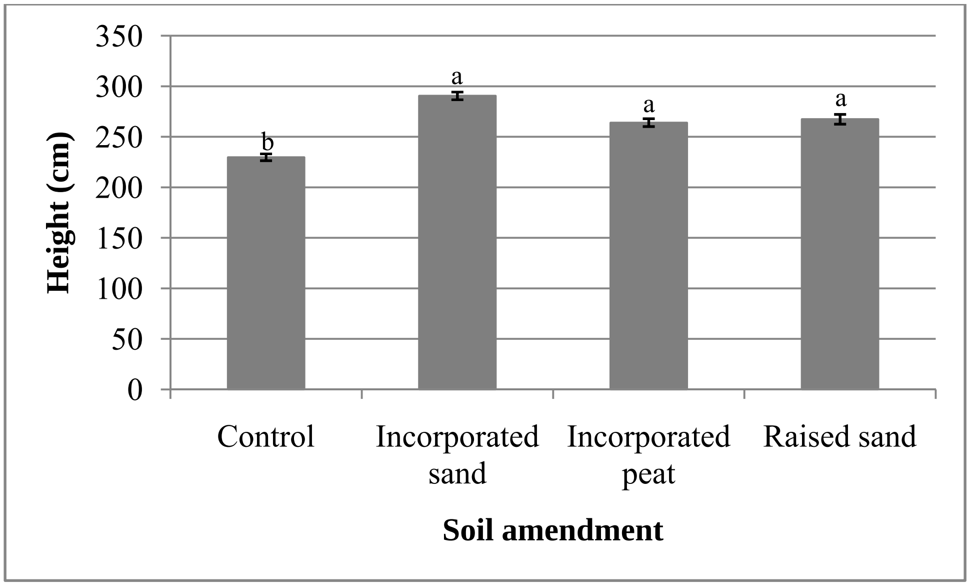

Fig. 3.3. Effect of soil amendment on final height of baldcypress (*Taxodium distichum* (L.) L. Rich.) after 27 months in field. Means±standard error (n = 6). Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand). Significance using the restricted maximum likelihood (REML) method (P = 0.001). Levels with same letter are not significantly different according to LSMeans Student's t test, $\alpha = 0.05$.

Planting depth and date of measurement had a significant (P=0.011, $P \leq 0.001$, respectively) main effect on pre-dawn stem water potential (Table 3.12). On average, trees planted 7.6 cm below grade had significantly more negative pre-dawn stem water potentials (-0.37 MPa) than trees planted at grade (-0.33 MPa) (Table 3.13). Across treatments, trees had significantly more negative stem water potentials (-0.54 MPa) on 10 Aug 2007 when compared to the other days. Trees on the 19 November 2006 had a less negative stem water potential (-0.21 MPa) than the other days that were measured.

Date of measurement and date x amendment significantly ($P \leq 0.001$, P=0.001, respectively) affected net photosynthetic activity (Table 3.14). Net photosynthetic activity main effects of soil amendment and planting depth were not significant, and there was no a significant soil amendment x planting depth interaction. Net

Table 3.12. Fixed effects test significance on pre-dawn stem water potential in baldcypress (*Taxodium distichum* (L.) L. Rich.) using the restricted maximum likelihood (REML) method.

Fixed effects test	Pre-dawn stem water potential
Depth[z]	0.011[y]
Amendment[x]	0.121
Amendment x Depth	0.668
Date[w]	<0.001
Date x Amendment	0.757
Date x Depth	0.252
Date x Amendment x Depth	0.852

[z]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).
[y]*P*-values.
[x]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).
[w]Dates that pre-dawn water potentials were measured: 17 June 2005, 29 June 2005, 2 August 2005, 7 November 2005, 28 April 2006, 31 July 2006, 19 November 2006, 8 June 2007, and 10 August 2007.

Table 3.13. Effect of planting depth and date measurement on pre-dawn stem water potential of baldcypress (*Taxodium distichum* (L.) L. Rich.).

Factor		Pre-dawn stem water potential (MPa)
Depth[z]	Above	-0.34±0.01[y]
	Grade	-0.33±0.01
	Below	-0.37±0.02
Date	17 June 2005	-0.33±0.02
	29 June 2005	-0.36±0.03
	2 August 2005	-0.38±0.01
	7 November 2005	-0.36±0.03
	28 April 2006	-0.31±0.01
	31 July 2006	-0.30±0.01
	19 November 2006	-0.21±0.01
	8 June 2007	-0.32±0.01
	10 August 2007	-0.54±0.03

[z]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).
[y]Means±standard error (n=3).

Table 3.14. Fixed effects test significance on net photosynthetic activity in baldcypress (*Taxodium distichum* (L.) L. Rich.) using the restricted maximum likelihood (REML) method.

Fixed effects test	Net photosynthetic activity
Depth[z]	0.243[y]
Amendment[x]	0.122
Amendment x Depth	0.383
Date[w]	<0.001
Date x Amendment	0.001
Date x Depth	0.299
Date x Amendment x Depth	0.919

[z]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).
[y]*P*-values.
[x]Soil amendments were one of the following: a native soil sandy loam (control), incorporated sand 30% by volume (incorporated sand) , incorporated composted peat 30% by volume (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).
[w]Dates net photosynthetic activity was measured: July 2005, November 2005, April 2006, July 2006, May 2007, and August 2007.

photosynthetic activity was significantly greater in July 2005, November 2005, and April 2006 when compared to May 2007 and August 2007 (Table 3.15). Net photosynthetic activity of trees in the control sections was lower than the other treatments in the first half of the experiment, but trees tended to be among the greatest in net photosynthetic rates in the later part of the study in general (Table 3.15).

Leaf chlorophyll concentration was significantly ($P \leq 0.05$) affected by soil amendment (Table 3.16). Planting depth did not significantly affect leaf chlorophyll concentration, and there was no significant soil amendment x planting depth interaction. Planting trees in the sand amendment in raised beds sections significantly reduced (59%, 63%, and 60%) chlorophyll a, chlorophyll b, and total leaf chlorophyll concentration, respectively, when compared to planting in incorporated peat sections.

Soil amendment significantly ($P \leq 0.05$) affected leaf N, P, Ca, Mg, S, Na, Zn, Cu, Fe, and Mo concentration (Tables 3.17 and 3.18). Planting depth significantly ($P \leq 0.05$) affected leaf Zn, Mn, Cu, and Fe concentration. There was a significant ($P \leq 0.05$) soil amendment x planting depth interaction for leaf N, K, Ca, Mg, S, Zn, Mn, Fe, and Mo concentration. Trees grown in the sand amendment in raised bed sections had significantly reduced leaf N (19.2 $g \cdot kg^{-1}$) and Mg (2.4 $g \cdot kg^{-1}$) concentrations when compared to trees grown in other soil treatments and significantly reduced leaf Cu (6.9 $\mu g \cdot g^{-1}$) concentrations when compared to trees grown in incorporated peat (10.1 $\mu g \cdot g^{-1}$) and control (9.8 $\mu g \cdot g^{-1}$) sections. Trees grown in incorporated sand amendment sections and sand in raised beds sections had significantly reduced leaf P (1.6 $g \cdot kg^{-1}$ and 1.5 $g \cdot kg^{-1}$, respectively) concentrations when compared to trees grown in control sections (1.8 $g \cdot kg^{-1}$). Trees grown in control sections or incorporated peat sections had significantly reduced leaf Ca (11.5 and 13.1 $g \cdot kg^{-1}$) concentration when compared to trees grown in sections with sand in raised beds (15.4 $g \cdot kg^{-1}$). Trees grown in sand in raised beds had significantly reduced leaf S (1.7 $g \cdot kg^{-1}$) concentration when compared to trees grown in incorporated sand sections (2.0 $g \cdot kg^{-1}$). Trees grown in control sections had significantly increased leaf Na (1.4 $g \cdot kg^{-1}$) and Zn (37.4 $\mu g \cdot g^{-1}$) concentrations when compared to trees grown in other sections. Trees grown in incorporated sand and peat sections had significantly reduced leaf Fe (111.2 $\mu g \cdot g^{-1}$ and 102.6, respectively) concentrations when compared to trees grown in the sand in raised beds (301.8 $\mu g \cdot g^{-1}$). Trees planted in sand in raised beds had significantly increased leaf Mo (9.1 $\mu g \cdot g^{-1}$) concentrations when compared to trees grown in other treatments. Trees planted 7.6 cm above grade had significantly increased leaf Zn concentration (32.0 $\mu g \cdot g^{-1}$) when compared to trees planted at grade (26.0 $\mu g \cdot g^{-1}$). Trees planted at grade had significantly increased leaf Cu concentrations (10.2 $\mu g \cdot g^{-1}$) when compared to trees planted 7.6 cm above grade (7.7 $\mu g \cdot g^{-1}$). Trees planted 7.6 cm below grade had significantly increased leaf Mn concentration (88.1 $\mu g \cdot g^{-1}$) when compared to trees planted at grade (77.6 $\mu g \cdot g^{-1}$). Trees planted 7.6 cm below grade had significantly increased leaf Fe concentration (259.7 $\mu g \cdot g^{-1}$) when compared to trees planted at grade (111.2 $\mu g \cdot g^{-1}$) or 7.6 cm above grade (146.3 $\mu g \cdot g^{-1}$).

In root cores collected from 7.5±2.5 cm depth, soil amendment and planting depth did not significantly affect total fine root length, average fine root diameter, fine root dry mass, or specific root (fine) length (SRL), and there was no significant soil amendment x planting depth interaction (Table 3.19).

Table 3.15. Effect of soil amendment and date measured on net photosynthetic activity of baldcypress (*Taxodium distichum* (L.) L. Rich.).

	Net photosynthetic activity ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$)					
Amendment	July 2005	November 2005	April 2006	July 2006	May 2007	August 2007
Control	9.1±0.5[y]	7.9±0.9	9.1±0.7	6.9±0.7	6.2±0.8	2.6±0.5
Incorporated sand	10.4±0.9	14.0±1.5	10.5±1.2	9.5±1.0	5.6±0.7	1.4±0.3
Incorporated peat	12.5±1.1	12.5±1.0	9.0±1.0	9.5±0.7	4.0±0.5	1.6±0.4
Raised sand	9.7±0.9	13.5±1.7	9.6±1.0	7.8±1.3	6.1±1.0	2.0±0.5

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[y]Means±standard error (n=6).

Table 3.16. Effect of soil amendment on chlorophyll concentration of baldcypress (*Taxodium distichum* (L.) L. Rich.).

Amendment[z]	Chlorophyll concentration ($\mu g \cdot g^{-1}$)		
	Chlorophyll a	Chlorophyll b	Chlorophyll total
Control	60.4±12.7[y]	16.0±3.5	76.4±16.2
Incorporated sand	66.2±10.2	16.7±2.7	82.9±12.9
Incorporated peat	77.0±9.8	21.9±3.0	98.9±12.7
Raised sand	31.8±2.8	8.1±0.9	39.9±3.6
Significance[x]			
Amendment	0.024	0.029	0.025

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

yMeans±standard error (n=6).

[x]Significance according to REML. *P*-values presented. Planting depth and planting depth x amendment interaction were nonsignificant.

In root cores collected from 15±2.5 cm depth, soil amendment significantly (P = 0.001, $P \leq 0.001$, and P = 0.023) affected total fine root length, fine root dry mass, and SRL, respectively, (Table 3.19). Planting depth significantly ($P \leq 0.05$) affected SRL. There was no significant soil amendment x planting depth interaction. Trees planted in sand amendment in raised bed sections had significantly greater total fine root length (15±2.5 cm depth) compared to trees planted in incorporated peat or control sections. Trees planted in sand amendments in raised bed sections had significantly greater fine root dry mass when compared to other soil treatments. Trees planted in incorporated sand and peat sections had significantly greater fine root dry mass when compared to trees planted in control sections. Trees in sand in raised beds had significantly lower SRL when compared to trees planted in other treatments. Trees planted with root collars at soil grade had significantly greater SRL when compared to trees planted 7.6 cm below soil grade.

In root cores collected from 7.5±2.5 cm depth, soil amendment significantly (P = 0.027) affected coarse root dry mass (Table 3.20). Planting depth did not significantly affect total coarse root length, average coarse root diameter, coarse root dry mass, or SRL (coarse), and there was no significant soil amendment x planting depth interaction.

Table 3.17. Effect of soil amendment and planting depth on leaf macronutrient and Na concentration of baldcypress (*Taxodium distichum* (L.) L. Rich.).

Amendment[z]	Planting depth[y]	N ($g \cdot kg^{-1}$)	P ($g \cdot kg^{-1}$)	K ($g \cdot kg^{-1}$)	Ca ($g \cdot kg^{-1}$)	Mg ($g \cdot kg^{-1}$)	S ($g \cdot kg^{-1}$)	Na ($g \cdot kg^{-1}$)
Control	Above	18.9±1.4[x]	1.7±0.3	9.6±0.1	11.8±1.2	2.9±0.2	1.8±0.1	1.8±0.9
	Grade	22.9±0.6	1.8±0.1	13.6±0.6	10.3±0.1	2.5±0.1	2.2±0.1	1.4±0.3
	Below	22.0±2.1	2.0±0.1	9.5±1.1	12.5±1.3	2.5±0.2	1.8±0.1	1.1±0.3
Incorporated sand	Above	20.0±0.5	1.6±0.1	9.5±0.9	14.3±0.9	2.5±0.1	1.9±0.1	0.5±0.1
	Grade	21.1±0.3	1.6±0.1	10.1±0.2	14.3±0.2	2.6±0.1	1.8±0.1	0.6±0.1
	Below	24.1±1.0	1.6±0.1	11.2±0.4	14.1±0.8	2.7±0.1	2.3±0.2	0.6±0.1
Incorporated peat	Above	22.0±1.3	1.8±0.1	10.0±0.6	14.1±0.7	2.8±0.0	1.9±0.1	0.8±0.2
	Grade	21.6±0.9	1.6±0.2	12.2±0.8	11.9±0.8	2.3±0.0	1.7±0.1	0.6±0.1
	Below	22.2±0.3	1.6±0.0	11.1±0.3	13.3±0.1	2.7±0.1	1.8±0.0	0.9±0.2
Raised sand	Above	20.8±0.2	1.4±0.0	12.1±1.1	13.3±0.3	2.1±0.1	1.7±0.0	0.3±0.0
	Grade	18.7±1.4	1.5±0.3	9.0±0.9	16.5±0.9	2.4±0.0	1.6±0.1	0.4±0.1
	Below	18.2±0.5	1.4±0.1	9.7±1.2	16.4±0.5	2.6±0.0	1.7±0.1	0.6±0.0
Significance[w]								
Amendment		0.012	0.018	0.437	<0.001	0.044	0.008	<0.001
Depth		0.286	0.995	0.205	0.214	0.222	0.430	0.768
Amendment x Depth		0.031	0.601	0.002	0.017	0.021	0.005	0.404

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[y]Root collars planted 7.6 cm above soil grade (above), at soil grade (grade), or 7.6 cm below soil grade (below).

[x]Means±standard error (n=3).

[w]Significance according to REML. *P*-values presented.

Table 3.18. Effect of soil amendment and planting depth on leaf micronutrient concentration of baldcypress (*Taxodium distichum* (L.) L. Rich.).

Amendment[z]	Planting depth[y]	Zn ($\mu g \cdot g^{-1}$)	Mn ($\mu g \cdot g^{-1}$)	Cu ($\mu g \cdot g^{-1}$)	Fe ($\mu g \cdot g^{-1}$)	B ($\mu g \cdot g^{-1}$)	Al ($\mu g \cdot g^{-1}$)	Mo ($\mu g \cdot g^{-1}$)
Control	Above	48.5±8.5	80.0±11.0	7.0±0.0	285.0±131.0	74.5±14.5	73.5±20.5	5.5±0.5
	Grade	27.3±4.4	77.3±3.5	12.7±2.4	123.0±6.0	71.0±6.5	61.0±4.0	4.7±0.7
	Below	36.3±2.7	80.0±0.6	9.7±1.2	113.7±11.6	66.7±2.7	64.0±12.5	7.7±0.7
Incorporated sand	Above	25.7±1.2	69.7±3.4	6.3±0.3	109.0±12.5	76.3±2.6	64.7±5.9	6.7±0.7
	Grade	29.3±0.9	80.7±3.8	11.3±0.3	108.3±7.9	83.7±2.7	65.3±4.8	7.7±0.3
	Below	27.7±2.4	98.7±10.1	10.0±0.6	116.3±9.4	89.0±8.1	72.0±7.8	5.7±0.3
Incorporated peat	Above	30.0±1.2	84.7±3.2	10.0±1.5	95.7±0.3	75.3±1.5	66.3±7.8	4.3±0.9
	Grade	24.0±2.9	76.3±2.3	10.3±2.3	103.0±1.7	72.7±4.4	69.7±6.0	6.3±0.3
	Below	23.0±2.0	94.0±2.1	10.0±1.2	109.0±4.7	80.3±1.2	67.0±7.1	7.3±0.9
Raised sand	Above	24.0±1.0	84.0±4.0	7.3±0.3	95.3±5.5	74.7±4.2	65.7±9.2	9.0±0.6
	Grade	23.3±1.2	76.0±5.9	6.3±0.3	110.3±3.8	70.0±2.9	84.0±19.3	11.0±0.6
	Below	32.0±2.5	79.7±2.7	7.0±0.0	699.7±173.1	83.3±9.2	51.0±8.7	7.3±0.9
Significance[w]								
Amendment		<0.001	0.430	0.017	<0.001	0.088	0.998	<0.001
Depth		0.016	0.011	0.033	0.003	0.321	0.646	0.105
Amendment x Depth		0.002	0.037	0.132	<0.001	0.522	0.464	<0.001

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).
[y]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).
[x]Means±standard error (n=3).
[w]Significance according to REML. *P*-values presented.

Table 3.19. Effect of soil amendment and planting depth on fine (average diameter < 1 mm) root production of baldcypress (*Taxodium distichum* (L.) L. Rich.) at 7.5 cm and 15 cm depths.

		Total root length (m)		Average root diameter (mm)		Root dry mass (mg)		Specific root length ($m \cdot g^{-1}$)	
Factor		7.5 cm	15 cm	7.5 cm	15 cm	7.5 cm	15 cm	7.5 cm	15 cm
Amendment[z]	Control	2.1±0.2[y]	1.3±0.1	0.47±0.01	0.47±0.01	54.9±4.7	29.2±2.5	40.7±2.4	45.7±2.5
	Incorporated sand	1.9±0.3	2.0±0.2	0.47±0.01	0.45±0.01	47.4±7.0	45.8±2.0	40.5±1.4	45.4±1.7
	Incorporated peat	2.7±0.3	1.8±0.1	0.48±0.00	0.45±0.01	74.1±8.8	40.9±3.8	37.2±1.3	46.2±1.8
	Raised Sand	2.2±0.3	2.8±0.3	0.51±0.01	0.48±0.01	63.7±9.0	72.8±9.2	35.0±1.2	38.8±1.2
Planting depth[x]	Above	2.1±0.2	2.0±0.2	0.48±0.01	0.46±0.01	54.2±6.5	48.6±6.9	40.0±1.6	44.8±1.5
	Grade	2.1±0.2	1.8±0.1	0.48±0.01	0.45±0.01	59.3±6.8	42.2±4.4	36.8±1.5	46.4±2.0
	Below	2.5±0.3	2.0±0.2	0.48±0.01	0.47±0.01	66.6±7.0	50.7±6.2	38.2±1.3	40.8±1.4
Significance[w]									
Amendment		0.313	0.001	0.075	0.092	0.086	<0.001	0.222	0.023
Depth		0.353	0.731	0.916	0.256	0.394	0.520	0.501	0.050

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[y]Means±standard error (n=3).

[x]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).

[w]Significance according to REML. *P*-values presented. There was no significant amendment x planting depth interaction.

Trees planted in the sand in raised beds sections had significantly greater coarse root dry mass when compared to trees planted in the incorporated sand sections. Root dry mass was intermediate in the incorporated peat sections.

In root cores collected from 15±2.5 cm depth, soil amendment significantly (P = 0.038) affected total coarse root length (Table 3.20). Planting depth significantly (P = 0.019 and 0.014) affected average coarse root diameter and SRL (coarse), respectively. There was no significant soil amendment x planting depth interaction. Trees planted in sand in raised beds sections had significantly greater total coarse root length when compared to trees planted in the control sections, with trees planted in incorporated peat or sand sections intermediate. Trees planted with root collars 7.6 cm below grade had significantly greater average coarse root diameter when compared to trees planted at grade. Trees planted with root collars at grade had significantly greater SRL when compared to trees planted with root collars 7.6 cm above or below grade.

Shoot DM was significantly (P = 0.027 and 0.043) affected by soil amendment and planting depth, respectively (Table 3.21). There was no significant ($P \leq 0.05$) soil amendment x planting depth interaction for shoot dry mass. Trees planted in the incorporated sand and sand in raised bed sections had significantly greater (41%) shoot DM when compared to trees planted in control sections. Trees planted in incorporated peat sections were intermediate for shoot DM. Trees planted at soil grade had greater (33%) shoot DM when compared to trees planted 7.6 cm below grade, with trees planted above grade being intermediate. Only one tree died in this study, and it was planted 7.6 cm below grade in one of the sections containing sand in a raised bed.

Planting depth significantly ($P \leq 0.001$) affected the number of potentially stem girdling roots (Table 3.21). Soil amendment did not have a significant effect and there was no significant soil amendment x planting depth interaction. Trees with root collars planted 7.6 cm above grade had a significantly greater number of potentially stem girdling roots (1.4 roots) when compared to planting root collars at soil grade (0.4 roots) or 7.6 cm below grade (0.2 roots).

Table 3.20. Effect of soil amendment and planting depth on coarse (average diameter ≥ 1 mm) root production of baldcypress (*Taxodium distichum* (L.) L. Rich.) at 7.5 cm and 15 cm depths.

		Total root length (m)		Average root diameter (mm)		Root dry mass (mg)		Specific root length ($m \cdot g^{-1}$)	
Factor		7.5 cm	15 cm	7.5 cm	15 cm	7.5 cm	15 cm	7.5 cm	15 cm
Amendment[z]	Control	0.25±0.03[y]	0.26±0.05	1.08±0.04	1.24±0.09	44.8±7.9	84.5±17.1	8.4±1.8	5.3±1.0
	Incorporated sand	0.25±0.04	0.30±0.03	1.08±0.08	1.19±0.08	39.9±5.4	109.2±21.4	6.7±0.9	4.2±0.7
	Incorporated peat	0.31±0.04	0.31±0.04	1.05±0.07	1.15±0.06	60.8±12.9	142.6±38.1	7.1±0.9	4.4±0.9
	Raised Sand	0.33±0.06	0.43±0.06	1.09±0.06	1.22±0.04	139.3±50.7	169.7±48.3	6.4±1.0	4.6±0.7
Planting depth[x]	Above	0.24±0.03	0.35±0.04	1.08±0.05	1.14±0.04	72.2±25.5	144.0±32.0	7.1±0.9	3.8±0.5
	Grade	0.34±0.04	0.32±0.04	1.16±0.05	1.11±0.06	93.1±31.5	93.1±22.2	7.0±1.4	6.4±0.9
	Below	0.27±0.04	0.31±0.04	0.99±0.06	1.34±0.07	48.3±9.3	142.4±32.6	7.5±0.7	3.6±0.5
Significance[w]									
Amendment		0.395	0.038	0.978	0.806	0.027	0.383	0.670	0.769
Depth		0.118	0.682	0.116	0.019	0.338	0.440	0.953	0.014

[z]Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), , or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[y]Means±standard error (n=3).

[x]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).

[w]Significance according to REML. *P*-values presented. There was no significant amendment x planting depth interaction.

Table 3.21. Effect of soil amendment and planting depth on shoot dry mass and potential stem girdling roots of baldcypress (*Taxodium distichum* (L.) L. Rich.).

Factor		Shoot dry mass (g)	Potential stem girdling roots[z]
Amendment[y]	Control	2271.1±401.3[x]	0.4±0.2
	Incorporated sand	3855.9±457.4	0.7±0.2
	Incorporated peat	3272.4±367.7	0.6±0.2
	Raised sand	3827.2±440.6	0.9±0.3
Planting depth[w]	Above	3389.8±438.7	1.4±0.2
	Grade	3889.1±351.2	0.4±0.1
	Below	2589.5±289.5	0.2±0.1
Significance[v]			
Amendment		0.027	0.407
Depth		0.043	<0.001

[z]Root angles from trunks were recorded on roots ≥ 2 cm in diameter and within the top 3 cm of the original root ball in order to determine the incidence of potential stem girdling roots.

[y]Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[x]Means±standard error (n=6).

[w]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).

[v]Significance according to REML. *P*-values presented. There was no significant amendment x planting depth interaction.

Coarse (≥2 cm diameter) root number in the NE quadrant was significantly (P = 0.019) affected by soil amendment (Table 3.22). Planting depth significantly (P = 0.011) affected coarse (≥2 cm diameter) root number in the SW quadrant. The total number of coarse (≥2 cm diameter) roots in all quadrants was significantly (P = 0.020 and 0.027) affected by soil amendment and planting depth, respectively (Table 3.22). There was no significant soil amendment x planting depth interaction. Planting trees in the incorporated peat and sand sections resulted in a greater number (1.9, 1.8 roots, respectively) of coarse (≥2 cm diameter) roots when compared to planting in control sections (0.6 roots) in the NE quadrant. Planting trees at soil grade resulted in a greater number (2.0 roots) of coarse (≥2 cm diameter) roots when compared to planting trees at 7.6 cm above grade (0.8 roots) in the SW quadrant. Planting trees in soils with incorporated peat and sand in raised beds sections resulted in a greater number (6.4 and 6.3 roots, respectively) of coarse (≥2 cm diameter) roots when compared to planting in control sections (3.6 roots). Planting trees at soil grade resulted in a greater number (6.8 roots) of coarse (≥2 cm diameter) roots when compared to planting trees at 7.6 cm above grade (4.7 roots) or below grade (5.0 roots). Coarse (2 cm > x > 1 cm diameter) root number was not significantly affected by soil amendment or planting depth, and there was no significant soil amendment x planting depth interaction (Table 3.22).

Discussion

Tree planting depth significantly affected plant growth. Trees planted 7.6 cm above grade had lower RGR_{height} than trees planted at soil grade or below grade during three measurement periods, and $RGR_{diameter}$ was variable among the planting depths. Planting below grade has been reported to negatively affect tree height and diameter in other studies, although there are mixed results depending on soil type and species. Arnold et al. (2007) reported that planting root collars 7.6 cm below grade in field (Boonville fine sandy loam) soil reduced height and trunk diameter in container-grown green ash (*Fraxinus pennsylvanica* Marsh.), crapemyrtle (*Lagerstroemia indica* L. x *Lagerstroemia fauriei* Koehne. 'Basham's Party Pink'), oleander (*Nerium oleander* L. 'Cranberry Cooler') and vitex (*Vitex agnus-castus* L. 'LeCompte'). However, sycamore (*Platanus occidentalis* L.) had a significantly greater height and trunk diameter when planted 7.6 cm above grade compared to planting at grade (Arnold et al., 2007). Arnold et al. (2005) reported mean height for green ash after three growing seasons was reduced for trees transplanted 7.6 cm below grade compared to those planted at grade, while planting 7.6 cm above grade slightly increased height growth in comparison. Arnold et al. (2005) reported that height for bougainvillea goldenraintrees (*Koelreuteria bipinnata* A.R. Franchet) after two growing seasons was less in trees planted above grade or below grade compared to planting at grade. Bougainvillea goldenraintrees planted at grade had increased trunk diameters compared to those planted below grade, and initially those planted above grade also had increased trunk diameters compared to trees planted below grade (Arnold et al., 2005).

Table 3.22. Effect of soil amendment and planting depth on coarse root (≥ 2 cm and 2 > x > 1 cm diameter) production in baldcypress (*Taxodium distichum* (L.) L. Rich.).

		NW quadrant[z]		NE quadrant		SW quadrant		SE quadrant		Total	
Factor		Root number ≥2 cm	Root number 2>x>1 cm	Root number ≥2 cm	Root number 2>x>1 cm	Root number ≥2 cm	Root number 2>x>1 cm	Root number ≥2 cm	Root number 2>x>1 cm	Root number ≥2 cm	Root number 2>x>1 cm
Amendment[y]	Control	1.3±0.2[x]	1.5±0.4	0.6±0.2	2.2±0.5	0.8±0.2	2.5±0.4	0.9±0.3	2.1±0.3	3.6±0.4	8.3±1.1
	Incorporated sand	1.4±0.2	1.9±0.4	1.8±0.4	1.7±0.2	1.5±0.4	1.9±0.3	1.1±0.2	1.9±0.4	5.8±0.7	7.6±0.6
	Incorporated peat	1.7±0.3	2.1±0.2	1.9±0.4	1.9±0.4	1.4±0.2	2.1±0.5	1.4±0.3	2.4±0.4	6.4±0.7	8.5±0.8
	Raised sand	1.6±0.3	2.2±0.6	1.3±0.3	1.9±0.4	1.9±0.4	1.8±0.4	1.4±0.3	2.0±0.5	6.3±0.7	7.9±1.4
Planting depth[w]	Above	1.4±0.2	2.4±0.4	1.3±0.3	2.1±0.4	0.8±0.2	2.5±0.4	1.1±0.3	2.1±0.3	4.7±0.5	9.2±0.9
	Grade	1.8±0.3	2.0±0.4	1.8±0.3	2.0±0.4	2.0±0.3	2.0±0.3	1.3±0.2	2.3±0.4	6.8±0.7	8.2±1.0
	Below	1.3±0.2	1.3±0.2	1.1±0.2	1.7±0.2	1.4±0.2	1.8±0.3	1.3±0.3	2.0±0.3	5.0±0.5	6.8±0.7
Significance[v]											
Amendment		0.738	0.784	0.019	0.852	0.075	0.581	0.607	0.777	0.020	0.8983
Depth		0.404	0.209	0.170	0.640	0.011	0.239	0.914	0.859	0.027	0.141

[z]Each root ball was visually divided into four quadrants in cardinal directions and roots ≥ 2 cm in diameter and 2 cm > x > 1 cm were counted and recorded.

[y]Soil amendments were one of the following: a native soil sandy loam (control), incorporated (30% by volume) sand (incorporated sand), incorporated (30% by volume) composted peat (incorporated peat), or a sandy topsoil in a raised bed at 20 cm height (raised sand).

[x]Means±standard error (n=6).

[w]Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).

[v]Significance according to REML. *P*-values presented. There was no significant soil amendment x planting depth interaction.

Trees planted below grade in our study had 4% mortality, while trees planted at grade or above grade had 0% mortality. Other studies have reported increased mortality in trees planted below grade. Wells et al. (2006) reported a 50% mortality rate 2 years after transplanting balled-and-burlapped Yoshino cherry (*Prunus* x *yedoensis* Matsum.) trees with root flares at 15 cm or 31 cm below grade, and a 0% mortality in trees planted with root flares at grade. Broschat (1995) reported 60% mortality 15 months after transplanting container-grown pygmy date palm (*Phoenix roebelenii* O'Brien) with the original root ball 90 cm below grade, and 0% mortality in trees planted with root balls at grade. Arnold et al. (2007) reported a 33% (crapemyrtle), 50% (green ash), 33% (oleander), 50% (sycamore) and 0% (vitex) mortality 3 years after transplanting with root collars 7.6 cm below grade. Transplanting root collars at grade or 7.6 cm above grade resulted in 0% mortality for all species except for the sycamore planted at grade which resulted in 17% mortality (Arnold et al., 2007).

Trees grown in sand in the raised beds sections had significantly reduced leaf N and Mg concentrations when compared to trees grown in other soil treatments and significantly reduced leaf Cu concentrations when compared to trees grown in incorporated peat and control sections, possibly due to the low content in the sand amendment. Trees grown in the incorporated sand amendment sections and the sand in raised bed sections had significantly reduced leaf P concentration when compared to trees grown in control sections possibly due to the higher level of soil P in control sections. Trees grown in control sections had significantly reduced leaf Ca concentrations when compared to trees grown in sections with sand in raised beds, possibly due to the type of clay (montmorillonitic) on site. Montmorillonitic clays require greater Ca saturation (>70%) for adequate Ca availability compared to a kaolinitic clay (Havlin et al., 2005). Trees grown in sand in raised beds had significantly reduced leaf S concentrations when compared to trees grown in incorporated sand sections. Soil S reactions are dependent on the organic and microbial fractions in the soil, i.e. increasing soil organic matter and microbial activity increase SO_4^{-2} adsorption potential (Havlin et al., 2005). The sand in raised beds had very low organic matter content and microbial activity, (fungal and bacterial, Chapter II, Table 2.10), possibly resulting in the reduced leaf S concentration in the trees. Trees grown in control sections had significantly increased leaf Na, probably due to the poor leaching of irrigation salts through a comparatively heavy soil, and Zn concentrations, possibly due to the clay content, when compared to trees grown in other sections. Trees grown in the incorporated sand and peat sections had significantly reduced leaf Fe concentrations when compared to trees grown in the sand in raised bed sections, possibly due to the high Fe content in leaves of trees planted below grade. Trees planted in the sand in raised beds had significantly increased leaf Mo concentration when compared to trees grown in the other sections. This is possibly the result of the high pH in this section, as alkaline conditions enhances Mo uptake (Marschner, 1995).

Trees planted 7.6 cm above grade had significantly increased leaf Zn concentration when compared to trees planted at grade. This is possibly due to the high pH of the soil, and potential periodic poor aeration/flooding which can decrease Zn uptake (Havlin et al., 2005; Marschner, 1995). Trees planted above grade may have had a benifical wicking effect and enhanced aeration of the root ball, due to planting above grade. Trees planted at grade had significantly increased leaf Cu concentrations when compared to trees planted 7.6 cm above grade. This may be due to competition for the same carrier site with Zn (Havlin et al., 2005). Trees planted 7.6 cm below grade had significantly increased leaf Mn concentrations when compared to trees planted at grade, and had significantly increased leaf Fe concentrations when compared to trees planted at grade or 7.6 cm above grade. Goss et al. (1990) and Armstrong and Drew (2002) reported that if oxygen partial pressure decreases below a certain level in the soil, as you would expect with increasing depth and/or reduced pore size, root growth and function is often impaired by anoxic conditions. In general, soil oxygen content decreased in this study with increasing soil depth. Under these conditions the mobility of certain nutrients increases, specifically Fe and Mn, to potentially toxic levels, depending on the plant species (Armstrong and Drew, 2002). Broschat (1995) also reported higher foliar Fe concentrations in pygmy date palm when planted 90 cm below grade (Fe possibly due to the vicinity of the water table increasing the Fe solubility) compared to those at planting depths ranging from 0 to 60 cm below grade. In contrast to our study, Broschat (1995) reported that as planting depth increased, foliar Mn concentrations decreased consistently, due to the increased uptake of Fe possibly inhibiting uptake of Mn. Even though soil oxygen content decreased with increasing soil depth, the soil treatments were all above 5% when measured. This value was within the range of 2% to 10% reported to be in most drained upper levels in soils (Kozlowski and Davies, 1975). A soil oxygen content of 3% or less is reported to stop root growth in most plants (Kozlowski and Davies, 1975). Pirone (1972) reported that roots of baldcypress have low oxygen requirements, and are very tolerant to low soil oxygen. Drew (1988) reported that low oxygen concentrations in the soil strongly inhibit root nutrient uptake and transport to the shoots, including N, P, and K. Trees grown in the sand in raised beds sections had significantly reduced leaf N, but the oxygen content was at or above 10%, suggesting that another factor may have influenced N content (i.e. poor soil N content/availability).

Mills and Jones (1996) reported a survey range for baldcypress leaf nutrient concentration levels from collected trees that did not have any visual leaf deficiency or toxicity symptoms. Although there were significant differences between some treatments, all treatments were within or above the reported survey range for N (17.9 $g{\cdot}kg^{-1}$), P (1.4 $g{\cdot}kg^{-1}$), Mg (1.9 to 2.7 $g{\cdot}kg^{-1}$), S (1.7 $g{\cdot}kg^{-1}$), and Zn (22 $\mu g{\cdot}g^{-1}$) concentrations (Mills and Jones 1996). All treatments were above the survey range for K (4.4 to 5.1 $g{\cdot}kg^{-1}$), Na (0.072 $g{\cdot}kg^{-1}$), Mn (48 $\mu g{\cdot}g^{-1}$), B (48 $\mu g{\cdot}g^{-1}$), Cu (5 $\mu g{\cdot}g^{-1}$), Al (.041 $\mu g{\cdot}g^{-1}$), and Mo (0.03 $\mu g{\cdot}g^{-1}$). The control sections were below survey range for Ca (13.7 to 19.8 $g{\cdot}kg^{-1}$), possibly due to the type of clay (montmorillonitic) on the site.

Generally, the finer, most external roots are the roots that are responsible for nutrient and water uptake (Eissenstat and Yanai, 1997). Because of their function, and higher turnover rates, fine roots strongly influence soil, carbon, water, and nutrient fluxes in the landscape (Eissenstat and Yanai, 1997; Gill and Jackson, 2000). Trees planted in sand in raised bed sections had greater total fine root length and fine root dry mass compared to trees planted in incorporated peat or control sections possibly as a result of reduced mechanical resistance in the sandy topsoil or due to increased soil temperatures compared to other amendments. Most root growth, depending on species, occurs at temperatures from 19 to 28 °C, although there may be some ecotypic variation in plant response (McMichael and Burke, 2002). Although all sections were above this range, root growth could have responded positively to the 2 °C increase in soil temperature in the sections with sand in raised beds. Planting trees in the incorporated peat and sand in raised bed sections resulted in a greater number of coarse (≥ 2 cm diameter) roots when compared to planting in control sections. Possibly as a result of increased fine root length and dry mass, as well as coarse roots, trees planted in the incorporated sand and sand in raised beds sections had significantly greater shoot DM when compared to trees planted in the other sections.

Planting trees at soil grade resulted in a greater number of coarse (≥ 2 cm diameter) roots when compared to planting trees above grade or below grade. Coarser, higher order roots provide the framework for nutrient and water transportation and the strength needed to anchor trees (Eissenstat and Yanai 1997). This may be why trees planted 7.6 cm below grade had significantly more negative pre-dawn stem water potentials than trees planted at grade. Trees planted at soil grade had greater shoot DM when compared to trees planted below grade, with trees planted above grade being intermediate.

Trees with root collars planted 7.6 cm above grade had a significantly greater number of potentially stem girdling roots when compared to planting root collars at soil grade or 7.6 cm below grade. These potentially girdling roots could be forming in trees planted above grade for stabilization. In contrast, Wells et al. (2006) reported that the occurrence of girdling roots in red maple (*Acer rubrum* L.) increased as planting depth increased with 14%, 48%, and 71% occurrence on trees planted at grade, 15 cm below grade, and 31 cm below grade, respectively.

Conclusion

Planting trees in the incorporated sand and sand in raised bed sections resulted in trees with greater RGR_{height}, $RGR_{diameter}$, total fine root length, fine root dry mass, and shoot DM. Trees planted above grade had decreased RGR_{height}, coarse roots, and a greater incidence of potentially girdling roots when compared to trees planted at or below grade. Planting trees at soil grade resulted in trees with greater shoot DM, reduced mortality, and less negative stem water potentials when compared to trees planted below grade. Although varying in severity, adverse effects of below grade planting were present across soil types, the severity of adverse effects of below grade planting was greatest in the higher clay content control soil than in raised beds with sandy soils.

CHAPTER IV
EFFECT OF PLANTING DEPTH DURING CONTAINER PRODUCTION AND SUBSEQUENT LANDSCAPE ESTABLISHMENT ON GROWTH OF LACEBARK ELM

Introduction

Landscape trees are increasingly being produced in container nursery systems in comparison to traditional field production practices (USDA, 2004). Container production of landscape trees has many advantages over traditional field grown practices, including less damage to the root system at transplanting and thus potentially better transplant quality/establishment, decreased production cost (labor and land), and increased marketability (Mathers et al., 2007). However, the inability to adequately quantify the effects of relatively small yet cumulatively significant changes in planting/transplanting depth during container production (potting–up/up-canning) threatens plant growth, marketability, aesthetic value, and/or performance, both during container production and in the landscape. Variability in planting depth is of particular concern, specifically the location of the root collar relative to soil grade, as optimum planting depth may vary among species, and may be dependent on cultural practices and/or environmental conditions (Arnold et al., 2005; Ball, 1999; Browne and Tilt, 1992; Drilias et al., 1982; Gilman and Grabosky, 2004; Pirone et al., 1988). We suggest that trees are frequently planted inappropriately during container production as a result of numerous interrelated nursery practices, including; 1) inappropriate size of plant material to container size ratio at up-canning, 2) shrinkage and loss of substrate, 3) excessive filling of container and compaction of substrate, 4) inappropriate irrigation practices, 5) hiding graft union, pruning scars, and 6) general carelessness.

It is suggested that if trees are planted too deep in the production phase, then the detrimental effects may be compounded during landscape installation (Fare, 2005). The few studies done thus far show contrasting results depending on container size, compounding effects of planting depths, and species used during container production (Fare, 2005; Giblin et al., 2005; Gilman and Harchick, 2008). Our goal in this study was to determine if planting too deep in container production through two up-canning events would affect subsequent landscape performance. Also we wanted to determine if trees were initially planted too deep in container production, and then brought back to grade in container production or when placed in the landscape, would the landscape establishment be affected. Therefore, a series of experiments was conducted on lacebark elm (*Ulmus parvifolia* Jacq.), a common landscape tree in urban environments, in order to determine the effects of different transplanting depths during container production and subsequent effects on landscape establishment.

Materials and Methods

EXPERIMENT 4.1. EFFECT OF PLANTING DEPTH DURING CONTAINER (10.8-L) PRODUCTION

Cultural Conditions

Ulmus parvifolia seeds were collected in College Station, Texas (lat. 30°37.78'N. long. 96°20.51'W.) in late November 2004, and stored in the dark in a cold room (Bally Case and Cooler, Inc.) at 2 °C until required. Seeds were soaked for 48 h in aerated (RENA® Air 100 Pump, Aquarium Pharmaceuticals, Inc., Chalfont, PA) citric acid (EM Science, EM Industries, Inc., Gibbstown, NJ) solution (100 $mg \cdot L^{-1}$). Seeds were rinsed in reverse osmosis (RO) water and planted in black plastic flats 10 cm x 36 cm x 51 cm black, plastic flats (Dyna-flat™, Kadon, Corp., Dayton, OH) containing a commercial substrate (Metro-Mix® 700 Series, Sun Gro®, Bellevue, WA) and then placed in a greenhouse at Texas A&M University, College Station. Emerging seedlings were fogged [Fogg-It Nozzle (3.785 $L \cdot min^{-1}$), Fogg-It Nozzel Co., San Francisco, CA] manually as required with reverse osmosis (RO) water.

Uniform seedlings (approximately 1.5 cm in height) were transplanted, after approximately 16 d, into 0.295 L green plastic containers (Dillen Products, Middlefield, OH) with their root collar at substrate surface (grade) (Metro-Mix® 700 Series, Sun

Gro®). Transplanted seedlings were maintained under shade (55% light exclusion) in a graveled nursery at Texas A&M University Horticultural Gardens. Seedlings were fertigated (0.27 $L \cdot min^{-1}$ flow rate) as required with sulfuric acid-injected water (pH 6.3-6.5) containing 50 $mg \cdot L^{-1}$ of N from a water soluble fertilizer (Peter Professional® Acid Special water soluble fertilizer, 21N-3.1P-5.8K, Scott's Company, Marysville, OH).

Young trees (liners) (approximately 10 cm in height) were transplanted after 50 d into 2.6-L (#1) black plastic containers (C-300S Classic, Nursery Supplies, Inc., Chambersburg, PA) with their root collars at substrate (composted pine bark mulch; Earth's Finest Black Diamond Mulch, The LetCo Group) surface (grade). Container substrate had the following characteristics: 59.2% organic matter, pH 5.8, electrical conductivity (EC) 0.862 $dS \cdot m^{-1}$, and nutrient levels with the following $mg \cdot g^{-1}$: 7.4 N, 0.8 P, 1.7 K, 12.1 Ca, 1.4 Mg, 0.1 Zn, 4.0 Fe, 0.3 Mn, 0.01 Cu, and 2.8 Na (Soil, Water, and Forage Testing Laboratory, College Station, TX). Container substrate was amended with the following, 7 $kg \cdot m^{-3}$ 15N-3.9P-9.9K controlled release fertilizer (Scotts Osmocote®Plus 15-9-12, Scotts-Sierra Horticultural Products Co., Marysville, OH), 4 $kg \cdot m^{-3}$ dolomitic limestone (Austin White Lime Company, Austin, TX), 2 $kg \cdot m^{-3}$ gypsum (Hoedown™ Standard Gypsum LP, Fredericksburg, TX), and 1 $kg \cdot m^{-3}$ micronutrients (Scotts Micromax® micronutrients, Scotts-Sierra Horticultural Products Co., Marysville, OH). Bulk density of the amended substrate was 0.25±0.01 $g \cdot cm^{-3}$. Liners were maintained in the nursery under shade and fertigated as previously described.

Trees were transplanted, after approximately 100 d in 2.6-L containers, into 10.8-L (#3) black, plastic containers (1200C Classic, Nursery Supplies, Inc.) with their root collars at substrate surface (grade), 5 cm below grade, or 5 cm above grade (Fig. 4.1A). Trees were maintained in the nursery under shade and fertigated as previously described. Average daily maximum/minimum temperature and precipitation were 23.02±0.45/10.43±0.47 °C and 0.21±0.06 cm, respectively. Trees were staked (1.2 m bamboo stakes; Tonkin Bamboo Cane, Welli Tonkin Bamboo Export Co., Ltd., Shenzhen, China) and tied (Tapener® HT-B2 Max®, Max Co. Ltd., Tokyo, Japan).

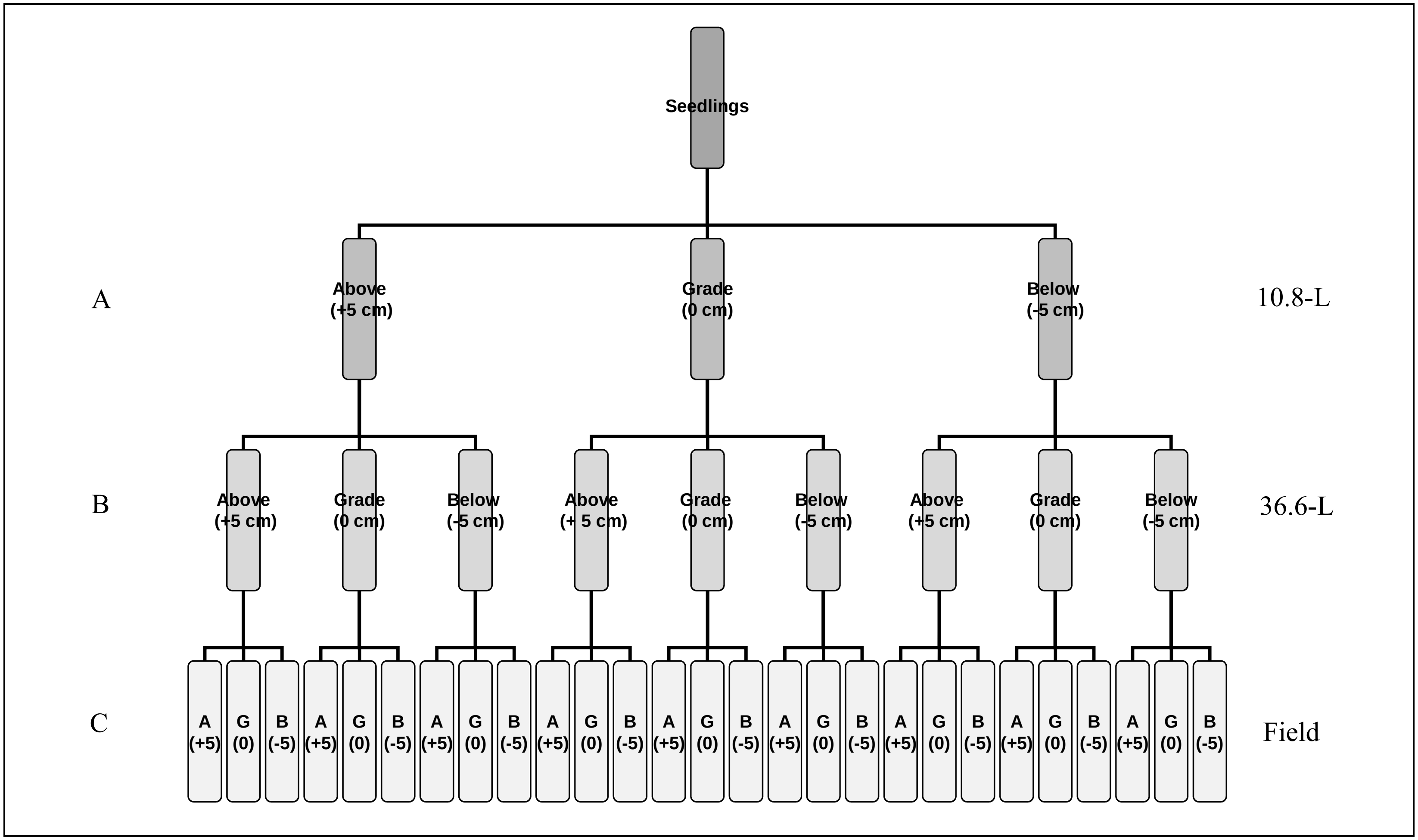

Fig. 4.1. Experimental design for experiment 4.1 (A), 4.2 (B), and 4.3 (C): Effect of planting depth during container production on landscape establishment of lacebark elm (*Ulmus parvifolia* Jacq.).

Plant Growth Parameters

Growth measurements were recorded on randomly selected trees at harvest (n = 7) approximately 200 d after transplanting into 10.8 L black plastic containers, and included tree height (from substrate grade to apical tip), trunk diameter (approximately 15 cm above existing soil line), and leaf, stem, root, and total plant dry mass (DM). Tissue samples were dried (Model 214330, Tru-Temp Oven, Hotpack Corporation, Philadelphia, PA) for 7 d at 70 °C and leaf, stem, root, and total DM (Model 1601A MP8-1, Sartorius Balances & Scales, Sartorius Corporation, Goettingen, Germany) were recorded.

Pre-dawn stem xylem water potential (n = 3) using a pressure chamber (Model 610, Pressure Chamber Instrument, Pressure Moisture System, PMS Instrument Co., Corvallis, OR) was determined at harvest.

Net photosynthetic activity was determined on three randomly selected trees per treatment (one leaf per tree; three readings per leaf) at harvest with a portable photosynthesis system (LI6400, LI-COR, Lincoln, NE), with red/blue LED light source (LI6400-02B) at photosynthetically active radiation (*PAR*) levels of 600 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (leaves saturated according to light response curve), and CO_2 concentration of 360 $\mu mol\ mol^{-1}$ from fully turgid, expanded, uniform, semi-mature leaves. Leaf temperature inside the leaf cuvette (2 cm^2 leaf area) was maintained at 25 °C.

Leaf chlorophyll content was determined at harvest (n = 7), by extraction of chlorophyll with acetone (Harborne, 1973). This procedure was modified as follows, five leaf discs (0.19 cm^2) per tree were collected from representative semi-mature leaves, placed in 5 mL of 80% acetone (Mallinckrodt Lab. Chemicals, Phillipsburg, NJ), and stored in the dark for 7 d at 4 °C. Supernatant was quantified with a spectrophotometer (Beckman Coulter™ Du® Series 640 UV/Vis Spectrophotometer, Beckman Coulter, Inc. Fullertan, CA) at 645 and 663 nm, and compared to an 80% acetone blank standard. Total chlorophyll content was expressed as $\mu g \cdot cm^{-2}$.

Statistical Design

The experiment was a completely randomized design, with three planting depths, surface (grade), 5 cm below grade, or 5 cm above grade. There was one *U. parvifolia* tree per container, with each container as a single replicate. Data was analyzed using analysis of variance (ANOVA) in the JMP system for Windows (Release 7.02, SAS Institute Inc., Cary, NC). The number of replications were: growth data (n=7), stem xylem water potential (n=3), net photosynthetic activity (n=3), and leaf chlorophyll content (n=7).

EXPERIMENT 4.2. EFFECT OF PLANTING DEPTH DURING CONTAINER (36.6-L) PRODUCTION

Cultural Conditions

Randomly selected trees from each treatment in experiment 4.1 (10.8 L) were transplanted, after approximately 200 d, into 36.6-L (#10) black plastic containers (4000C Classic, Nursery Supplies, Inc.) at the following depths, grade (existing soil/substrate line maintained), 5 cm below grade, or 5 cm above grade (Fig. 4.1B). Relation of original root collar (2.6-L) to soil/substrate line ranged from 10 cm below grade to 10 cm above grade. Container substrate (composted pine bark mulch; Earth's Finest Black Diamond Mulch, The LetCo Group) was amended as described previously. Trees were restaked (1.2 m bamboo stakes) and tied. Trees were maintained in the nursery under shade and fertigated as previously described. Average daily maximum/minimum temperature and precipitation were 32.85±0.29/21.66±0.30 °C and 0.35±0.08 cm, respectively.

Plant Growth Parameters

Growth measurements were recorded from randomly selected trees at harvest (n = 6) approximately 100 d after transplanting into 36.6-L black plastic containers, and included tree height (from soil line to apical tip), trunk diameter (approximately 15 cm above existing soil line), and shoot, root, and total plant dry mass (DM). Tissue samples were dried as described previously. Stem xylem water potential, net photosynthetic activity, and leaf chlorophyll content (n = 3) were determined at harvest, as previously described.

Statistical Design

The experiment was a completely randomized design, with nine planting depth treatments (Fig. 4.1B). There was one lacebark elm tree per container, with each container as a single replicate. Data was analyzed using analysis of variance (ANOVA) in the JMP system for Windows (Release 7.02, SAS Institute Inc., Cary, NC). The numbers of replications were: growth data (n = 6), stem xylem water potential (n = 3), net photosynthetic activity (n = 3), and leaf chlorophyll content (n = 3).

EXPERIMENT 4.3. EFFECT OF PLANTING DEPTH DURING CONTAINER PRODUCTION ON LANDSCAPE ESTABLISHMENT

Cultural Conditions

Randomly selected trees (36.6 L) from experiment 4.2 were transplanted, after approximately 100 d in 36.6-L containers, into the field (Boonville Series, fine, smectitic, thermic Chromic Vertic Albaqualfs) at the horticulture farm, College Station, Texas. The soil had a textural analysis of 77% sand, 11% silt, and 12% clay, contained 1.9% organic matter, pH 5.2, electrical conductivity (EC) 0.086 $dS \cdot m^{-1}$, and nutrient levels with the following $\mu g \cdot g^{-1}$: 8 N, 33 P, 64 K, 283 Ca, 36 Mg, 0.56 Zn, 133.3 Fe, 6.9 Mn, 0.29 Cu, 191 Na, 160 S, and 0.08 B. Trees were transplanted at the following depths, grade (existing soil/substrate line maintained), 5 cm below grade, or 5 cm above grade (Fig. 4.1C). Final relation of root collar to soil line ranged from 15 cm below grade to 15 cm above grade. Trees were drip-irrigated (T-Tape®, T-Systems Intl. Inc., San Diego, CA) as required. Average daily maximum/minimum temperature and precipitation were 25.64±0.41/14.98±0.43 °C and 0.35±0.06 cm, respectively (Office of the Texas State Climatologist, Department of Atmospheric Sciences, Texas A&M University, College Station, TX).

Plant Growth Parameters

Height, diameter, and leaf chlorophyll concentration (n = 6) were determined at harvest (365 d), as described previously.

Statistical Design

The experiment was a randomized complete block design, with twenty-seven planting depth treatments (Fig. 4.2C). Data was analyzed using analysis of variance (ANOVA) in the JMP system for Windows (Release 7.02, SAS Institute Inc., Cary, NC). The number of replications was: growth data and leaf chlorophyll concentration (n = 6).

Results

EXPERIMENT 4.1. EFFECT OF PLANTING DEPTH DURING CONTAINER (10.8-L) PRODUCTION

Planting depth significantly ($P \leq 0.001$, 0.025, 0.039, and 0.049) affected tree height, leaf DM, stem DM, and total DM, respectively (Fig. 4.2 and Fig. 4.3). Planting the root collar 5 cm below grade significantly reduced tree height (26% or 16%) when compared to planting the root collar at soil grade or 5 cm above soil grade, respectively (Fig. 4.2A). Planting depth did not significantly affect trunk diameter (Fig. 4.3B). Planting the root collar 5 cm below grade significantly reduced leaf DM (37%), stem DM (42%), and total DM (31%) when compared to planting the root collar at soil grade, but not root DM (Fig. 4.3).

Planting depth significantly (P=0.001) affected leaf chlorophyll concentration (Fig. 4.4A). Planting the root collar at soil grade or 5 cm above soil grade significantly reduced leaf chlorophyll concentration (20% and 16%, respectively) when compared to planting the root collar at 5 cm below soil grade. Planting depth significantly (P=0.027) affected net photosynthetic activity (Fig. 4.4B). Planting the root collar 5 cm above soil grade significantly reduced net photosynthetic activity (40% and 39%) when compared to planting the root collar at soil grade or 5 cm below grade, respectively. Planting depth did not significantly affect stem xylem water potential (Fig. 4.4C). There was 0% mortality across treatments.

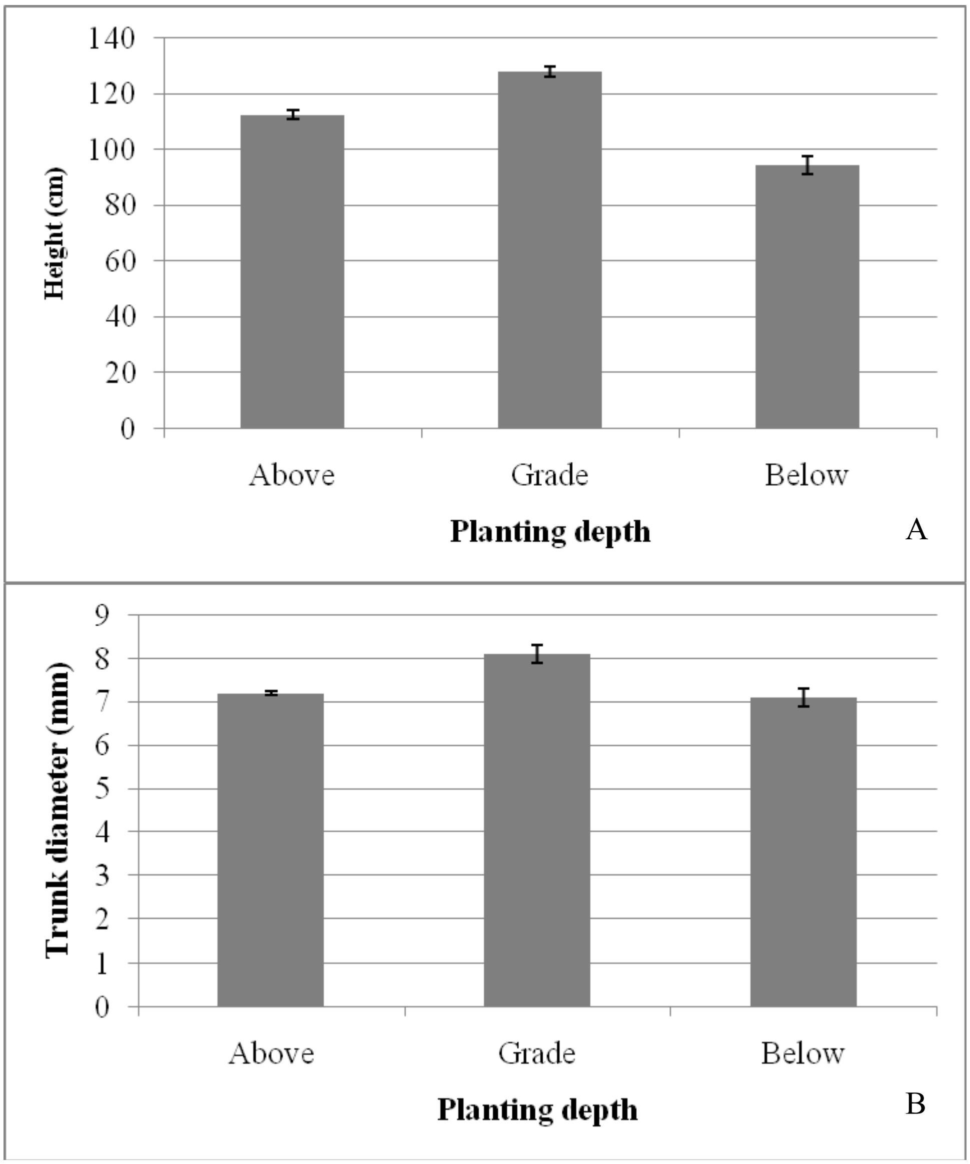

Fig. 4.2. Effect of planting depth on height (A) and trunk diameter (B) of lacebark elm (*Ulmus parvifolia*) after 200 d in 10.8 L containers. Root collars were planted 5 cm above soil grade (above), at soil grade (grade), or 5 cm below grade (below). Height was measured from soil line to apex of tree. Trunk diameter was measured 15 cm above soil/substrate line. Planting depth significantly ($P \leq 0.001$) affected tree height, but not trunk diameter. Means ± standard error (n = 7).

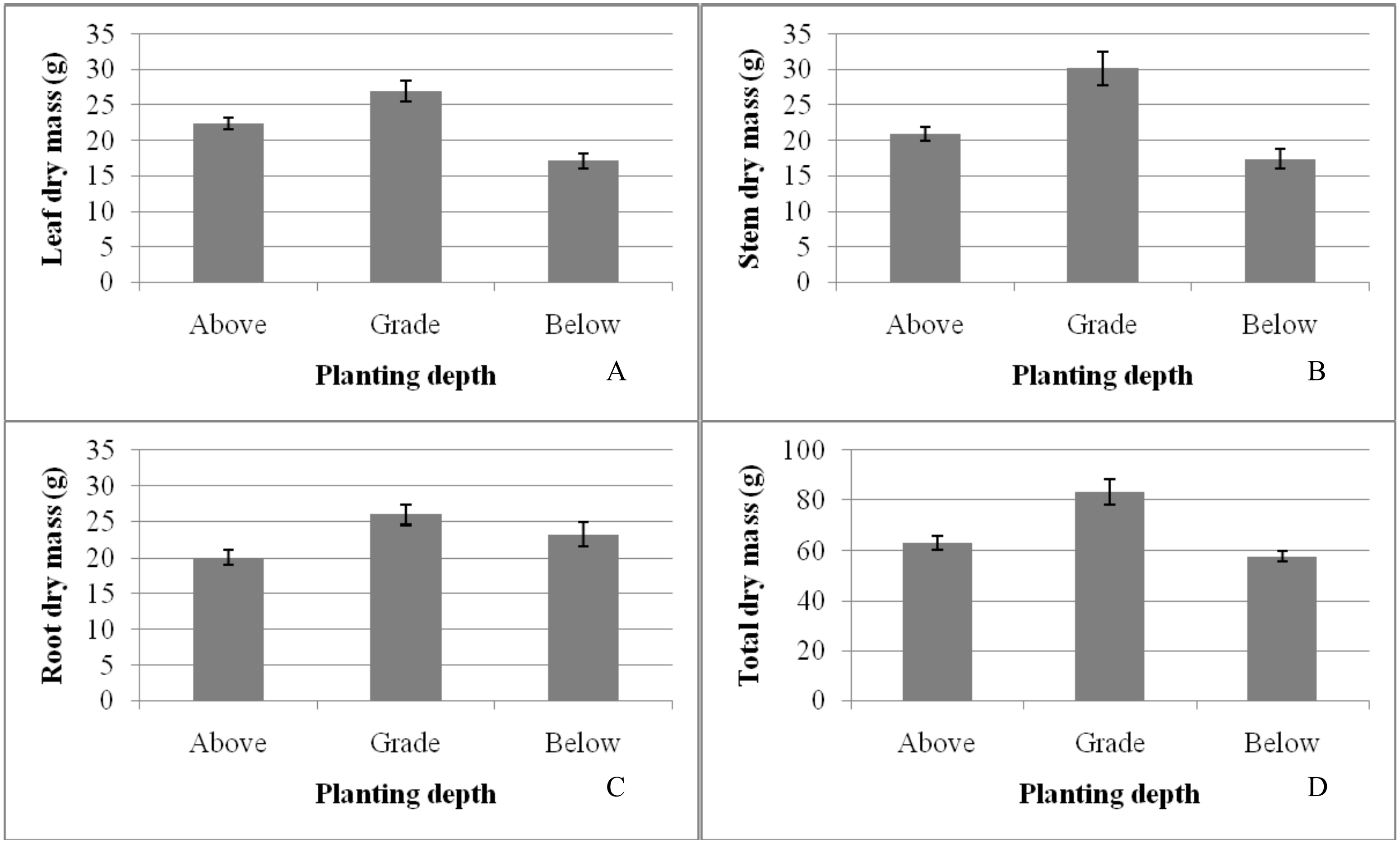

Fig. 4.3. Effect of planting depth on leaf DM (A), stem DM (B), root DM (C), and total DM (D) of lacebark elm (*Ulmus parvifolia* Jacq.) after 200 d in 10.8 L containers. Root collars were planted 5 cm above soil grade (above), at soil grade (grade), or 5 cm below grade (below). Planting depth significantly (P = 0.025, P = 0.039, P = 0.049) affected leaf DM, stem DM, and total DM, respectively, but not root DM (P = 0.343). Means ± standard error (n = 7).

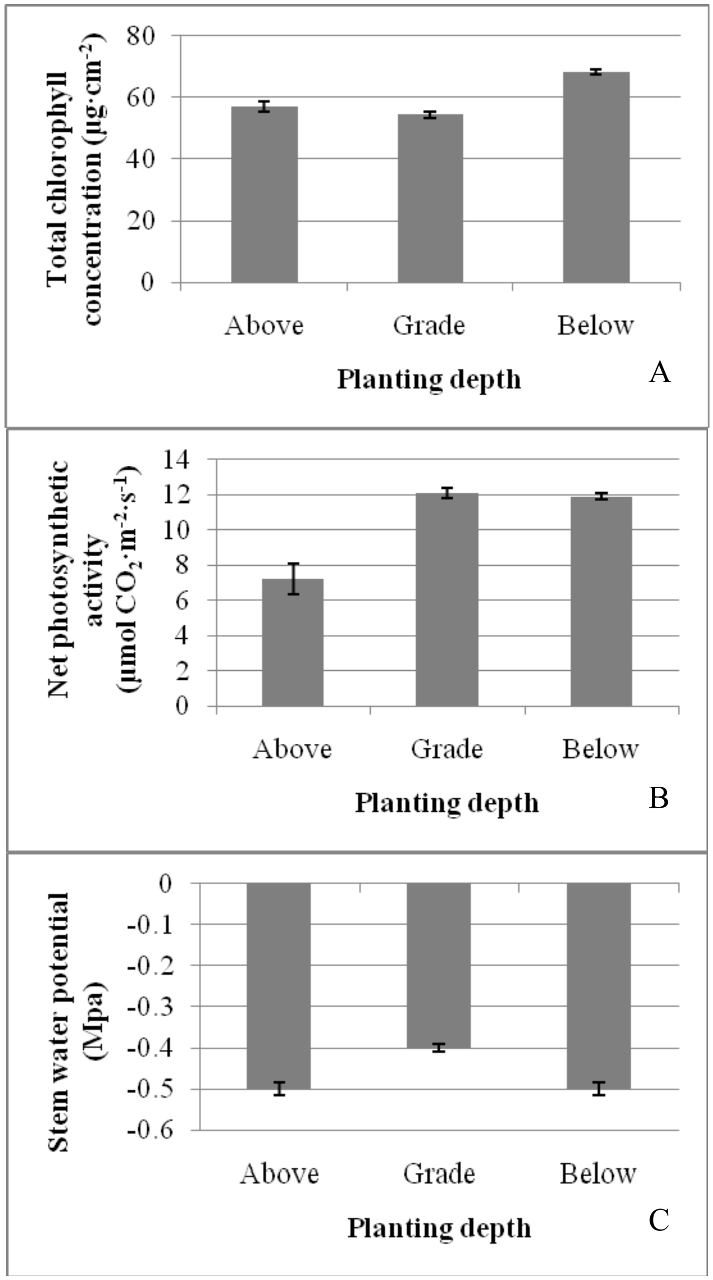

Fig. 4.4. Effect of planting depth on total chlorophyll concentration (A), net photosynthetic (Pn) activity (B), and pre-dawn stem water potential (C) of lacebark elm (*Ulmus parvifolia* Jacq.) after 200 d in 10.8 L containers. Root collars were planted 5 cm above soil grade (above), at soil grade (grade), or 5 cm below grade (below). Planting depth significantly (P = 0.001, P = 0.027) affected total chlorophyll concentration and net Pn activity, respectively, but not stem water potential. Means ± standard error (n = 7; n = 3 (net Pn)).

EXPERIMENT 4.2. EFFECT OF PLANTING DEPTH DURING CONTAINER (36.6-L) PRODUCTION

Planting depth significantly (*P* = 0.048) affected tree height (Fig. 4.5A) when all nine treatments were compared with each other. Trees planted BG (B = trees initially planted 5 cm below substrate grade in 10.8-L containers, and G = trees subsequently planted at substrate surface grade in 36.6-L containers) were significantly shorter (29 cm) than trees planted AB (A= trees initially planted 5 cm above substrate grade in 10.8-L containers; B= trees subsequently planted 5 cm below substrate surface grade in 36.6-L containers), AA, GG, or BB. Planting depth significantly (*P* = 0.004) affected trunk diameter (Fig.4.5B). Trees planted AA, GB, and BG had significantly smaller trunk diameters than those planted AB or BB. There was 0% mortality across treatments.

Planting depth significantly ($P = 0.020$, $P \leq 0.001$, $P \leq 0.001$) affected root DM, shoot DM, and total DM, respectively (Fig. 4.6). Trees planted AA had significantly reduced (39%) root DM when compared to trees planted AB (i.e. returned to a grade location at transplant). Trees planted GB, BG, and AA had significantly reduced (32% on average) shoot DM when compared to trees planted AB and BB. Trees planted AB had significantly greater (28%, 31%, 35%, and 37%) total DM when compared to trees planted GG, GB, BG, and AA, respectively.

Planting depth significantly (*P* = 0.038) affected total leaf chlorophyll concentration (Fig. 4.7). Trees planted BA and AA had significantly reduced (42% on average) total leaf chlorophyll when compared to trees planted GA, BB, AB, and GB. Planting depth significantly (*P* = 0.001) affected net photosynthetic activity (Fig. 4.8). Trees planted AG and AA had significantly reduced net photosynthetic activity compared to trees planted GG and GB. Planting depth significantly ($P \leq 0.001$) affected pre-dawn stem water potential (Fig. 4.9). Trees planted AA and BA had significantly more negative water potentials than trees planted GG and GA.

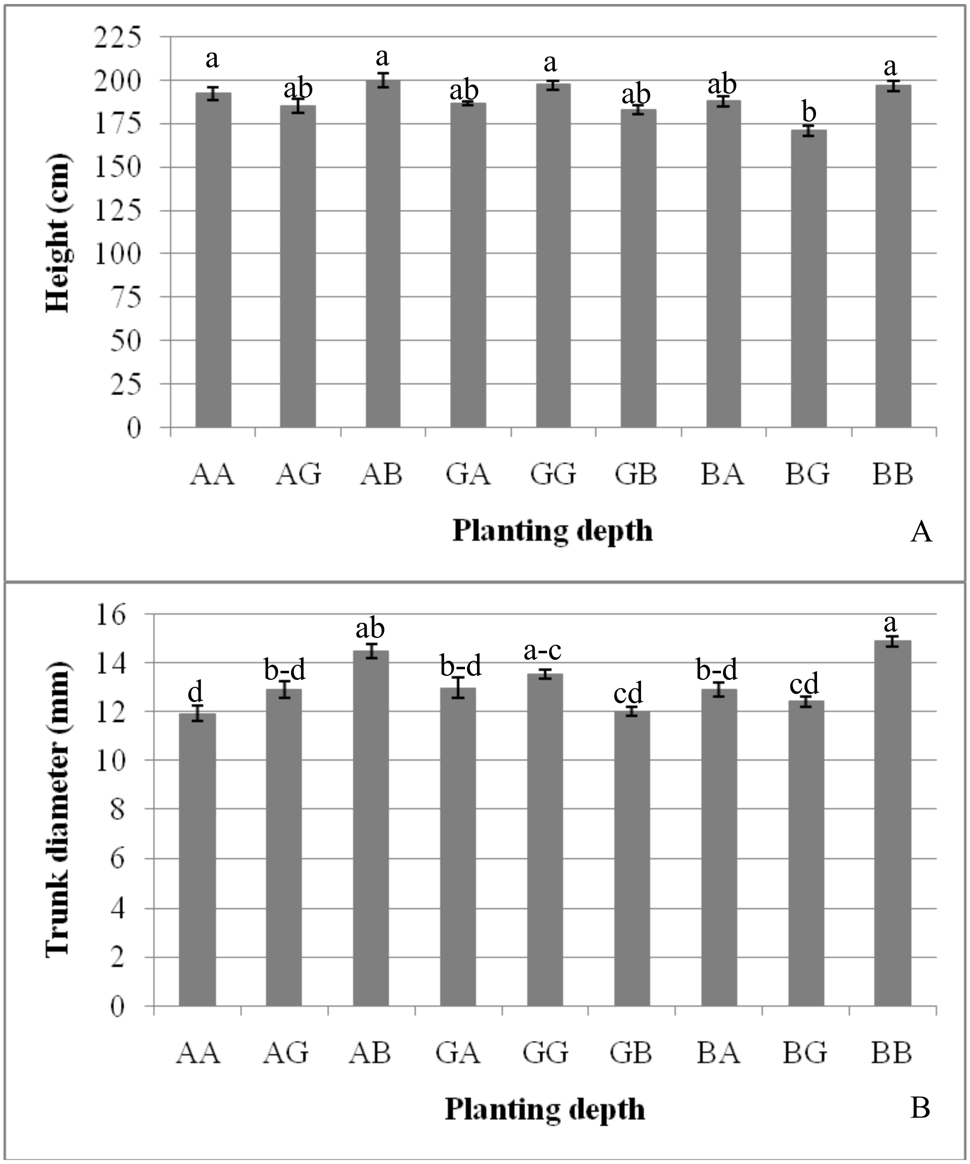

Fig. 4.5. Effect of planting depth on height (A) and diameter (B) of lacebark elm (*Ulmus parvifolia* Jacq.) 100 d after transplanting into 36.6-L containers. First letter = 10.8-L depth, Second letter = 36.6 L container planting depth. See figure 4.1 for clarification. Planting depth significantly (P = 0.048, P = 0.004) affected height and diameter, respectively. Means ± standard error (n = 6). Levels with same letter are not significantly different according to LSMeans Student's t test, α = 0.05.

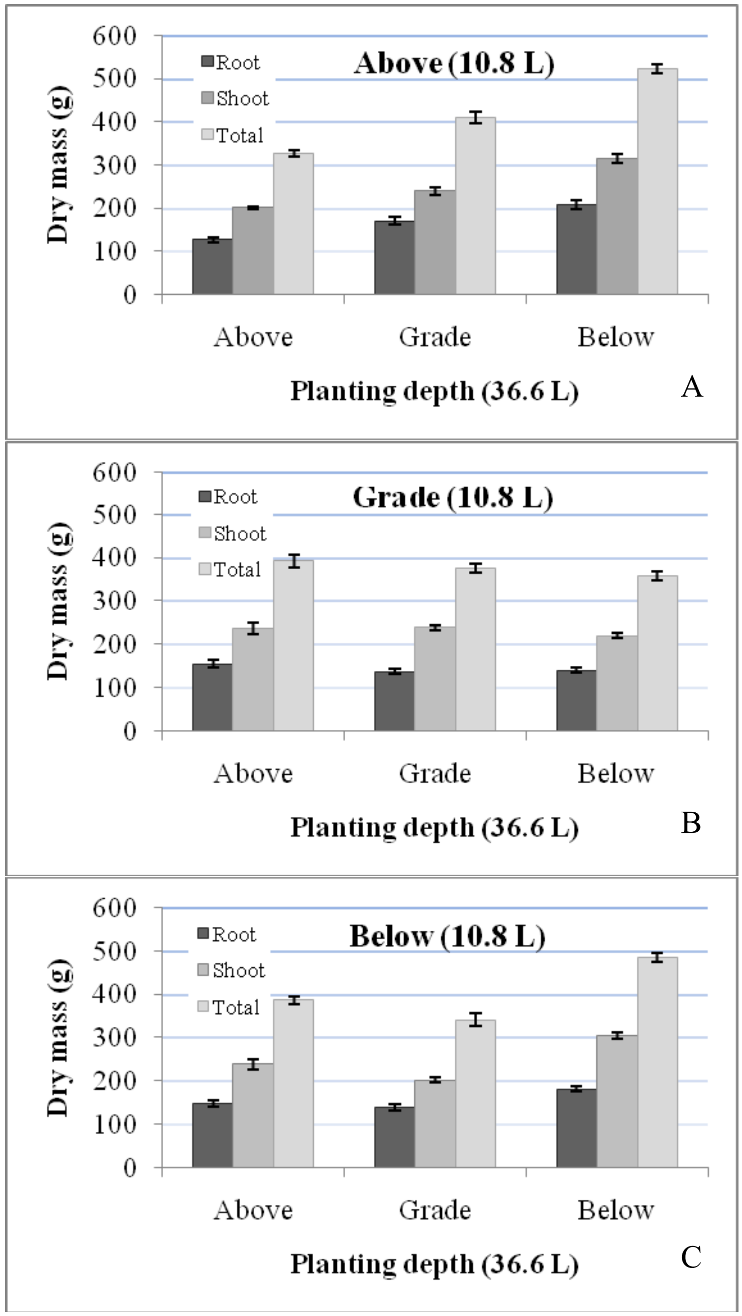

Fig. 4.6. Effect of planting depth on root, shoot, and total DM of lacebark elm (*Ulmus parvifolia* Jacq.) when initially transplanted (10.8 L) 5 cm above soil grade (A), at soil grade (B), or 5 cm below soil grade (C). Root collars were transplanted 5 cm above soil grade (above), at soil grade (grade), or 5 cm below grade (below) into 36.6 L. Planting depth significantly (P = 0.020, ≤0.001, ≤0.001) affected root DM, shoot DM, and total DM, respectively. Means ± standard error (n = 6).

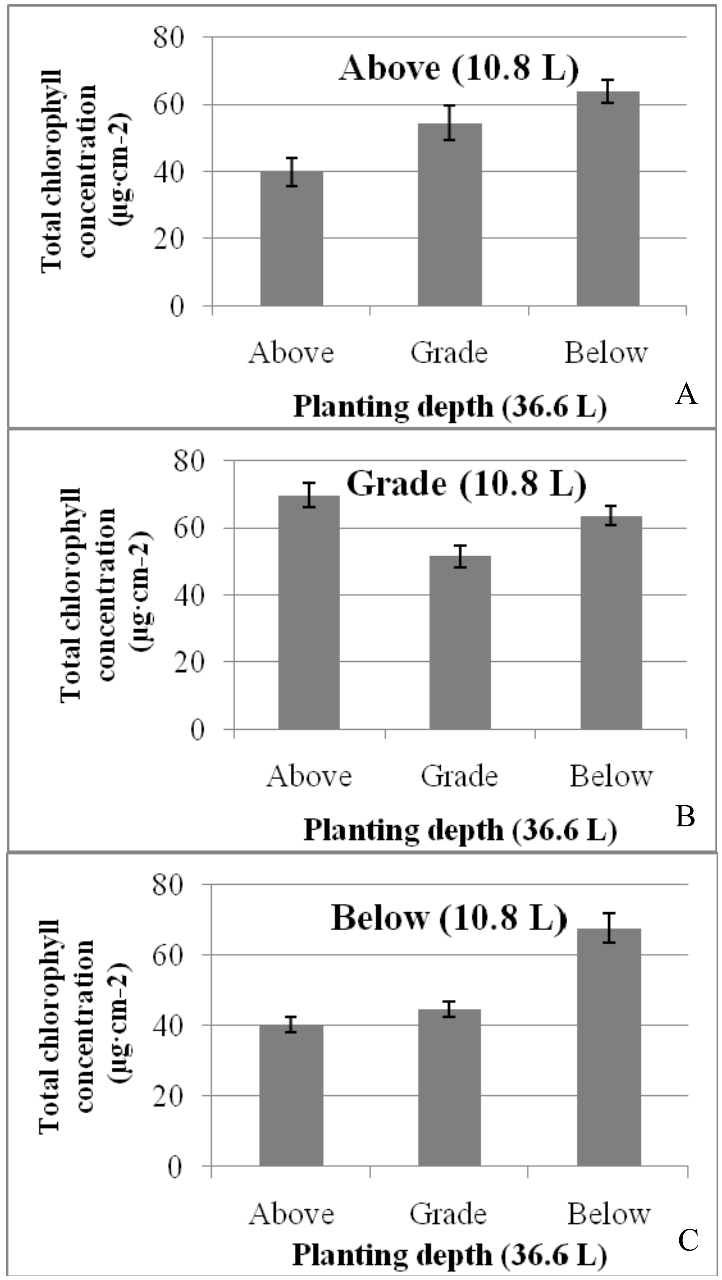

Fig. 4.7. Effect of planting depth on total chlorophyll concentration in lacebark elm (*Ulmus parvifolia* Jacq.) when initially transplanted (10.8 L) 5 cm above soil grade (A), at soil grade (B), or 5 cm below soil grade (C). Root collars were transplanted 5 cm above soil grade (above), at soil grade (grade), or 5 cm below grade (below) into 36.6 L. Planting depth significantly (P = 0.038) affected total chlorophyll concentration. Means ± standard error (n = 3).

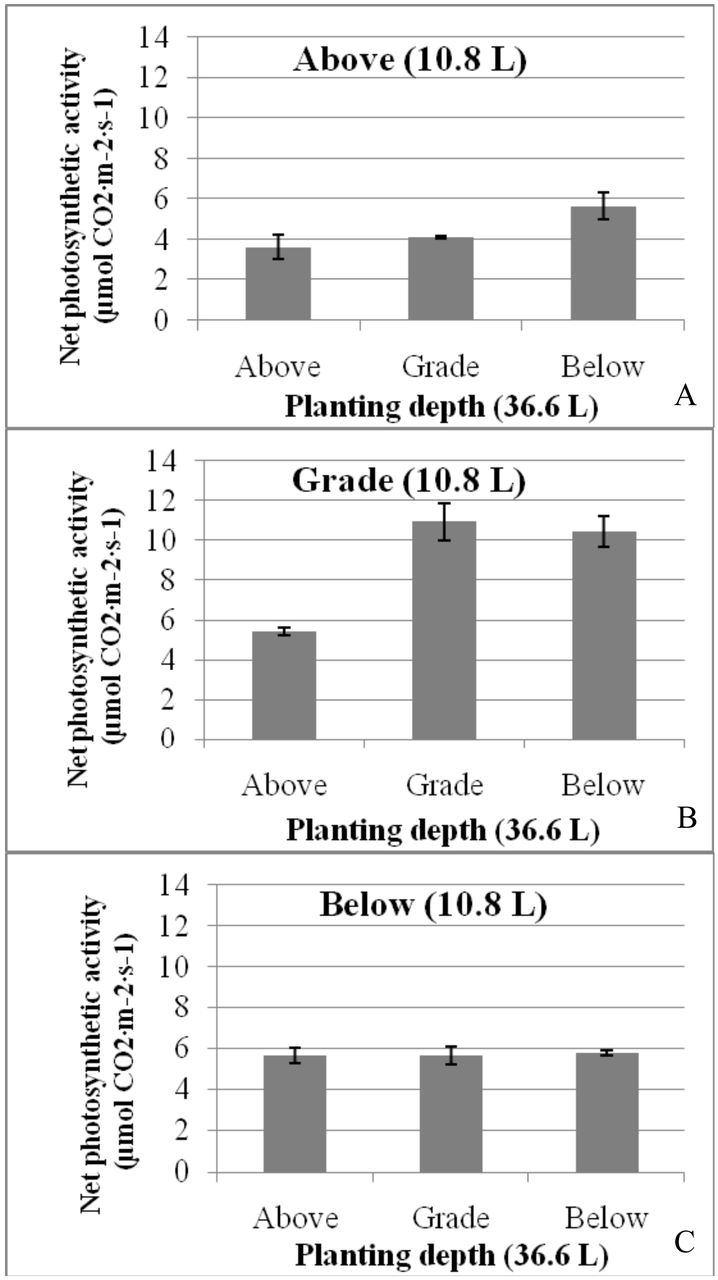

Fig. 4.8. Effect of planting depth on net photosynthetic activity in lacebark elm (*Ulmus parvifolia* Jacq.) when initially transplanted (10.8 L) 5 cm above soil grade (A), at soil grade (B), or 5 cm below soil grade (C). Root collars were transplanted 5 cm above soil grade (above), at soil grade (grade), or 5 cm below grade (below) into 36.6 L. Planting depth significantly (P = 0.001) affected net photosynthetic activity. Means ± standard error (n = 3).

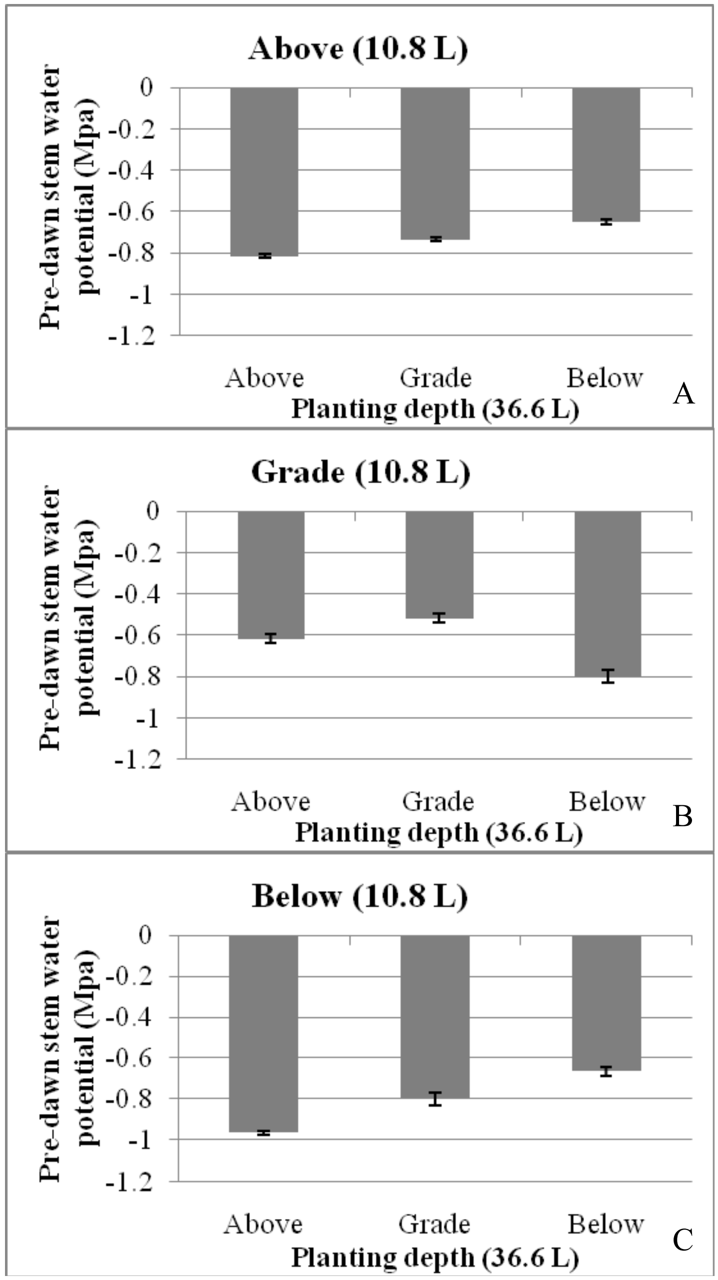

Fig. 4.9. Effect of planting depth on pre-dawn stem water potential in lacebark elm (*Ulmus parvifolia* Jacq.) when initially transplanted (10.8 L) 5 cm above soil grade (A), at soil grade (B), or 5 cm below soil grade (C). Root collars were transplanted 5 cm above soil grade (above), at soil grade (grade), or 5 cm below grade (below) into 36.6 L. Planting depth significantly ($P \leq 0.001$) affected pre-dawn stem water potential. Means ± standard error (n = 3).

EXPERIMENT 4.3. EFFECT OF PLANTING DEPTH DURING CONTAINER PRODUCTION ON LANDSCAPE ESTABLISHMENT

Planting depth did not significantly affect relative growth rate (RGR) in height or diameter of lacebark elm (Table 4.1). Date had a significant ($P \leq 0.001$) effect on RGR in height and diameter. Relative growth rate was higher from March 2007 - August 2007 when compared to August 2006 – March 2007 for height (Fig. 4.10) and diameter (4.11) (see appendices Fig. A.1 and A.2). Final height (Fig. 4.12) and diameter (Fig. 4.13) were significantly affected by planting depth ($P = 0.033$, $P = 0.048$, respectively). Planting trees GAG resulted in trees which were significantly taller than trees planted GAA. Trees planted ABG had significantly greater trunk diameters than trees planted GAA. Mean comparisons are presented in Fig. 4.12 and 4.13. Specific combinations of planting depths during production and field planting produced a wide range of responses for final heights and trunk diameters. However, excluding (BAA), four best treatments (ABA, GAG, GBA, BBA) for tree height had their root collars at or 5 cm above grade, while four of the five worst treatments had their root collars 5-15 cm below grade (ABB, BAB, BGB, BBB). The other poor performing treatment (GAA) may be excessively above grade by 10 cm. Planting depth did not significantly ($P = 0.562$) affect total leaf chlorophyll concentration in lacebark elm (data not shown). There was 0% mortality across treatments.

Table 4.1. Fixed effects test significance on relative growth rate (RGR) of height and trunk diameter of lacebark elm (*Ulmus parvifolia* Jacq.) using the analysis of variance (ANOVA) method.

Fixed effects test	RGR_{height}^{z}	$RGR_{diameter}^{y}$
Depth[x]	0.551	0.983
Date[u]	<0.001	<0.001
Date x Depth	0.075	0.461

[z]Relative Growth Rate (RGR) calculated according to Hoffmann and Porter (2002). Height measured from soil line to apex of tree.
[y]Trunk diameter measured 15 cm above soil/substrate line.
[x]Root collars planted 5 cm above soil grade (above), at grade (grade), or 5 cm below grade (below).
[w]*P*-values.
[u]Dates that height and diameter were measured: August 2006, March 2007, and August 2007.

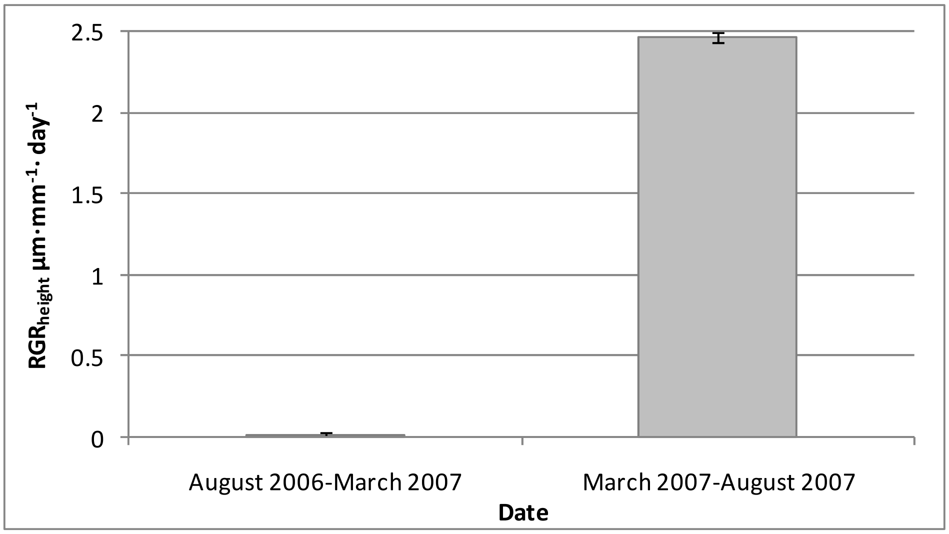

Fig. 4.10. Effect of date on relative growth rate in height (RGR_{height}) of lacebark elm (*Ulmus parvifolia* Jacq.) once transplanted to field. Relative growth rate (RGR) calculated according to Hoffmann and Porter (2002). Height measured from soil line to apex of tree. Means±standard error (n = 6).

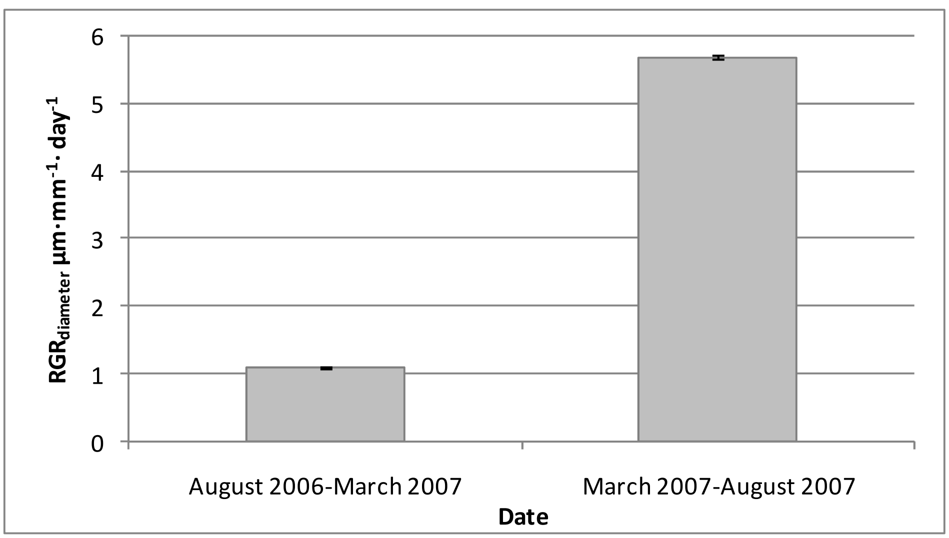

Fig. 4.11. Effect of date on relative growth rate in diameter ($RGR_{diameter}$) of lacebark elm (*Ulmus parvifolia* Jacq.) when transplanted to field. Relative growth rate (RGR) calculated according to Hoffmann and Porter (2002). Trunk diameter measured from soil/substrate line. Means±standard error (n = 6).

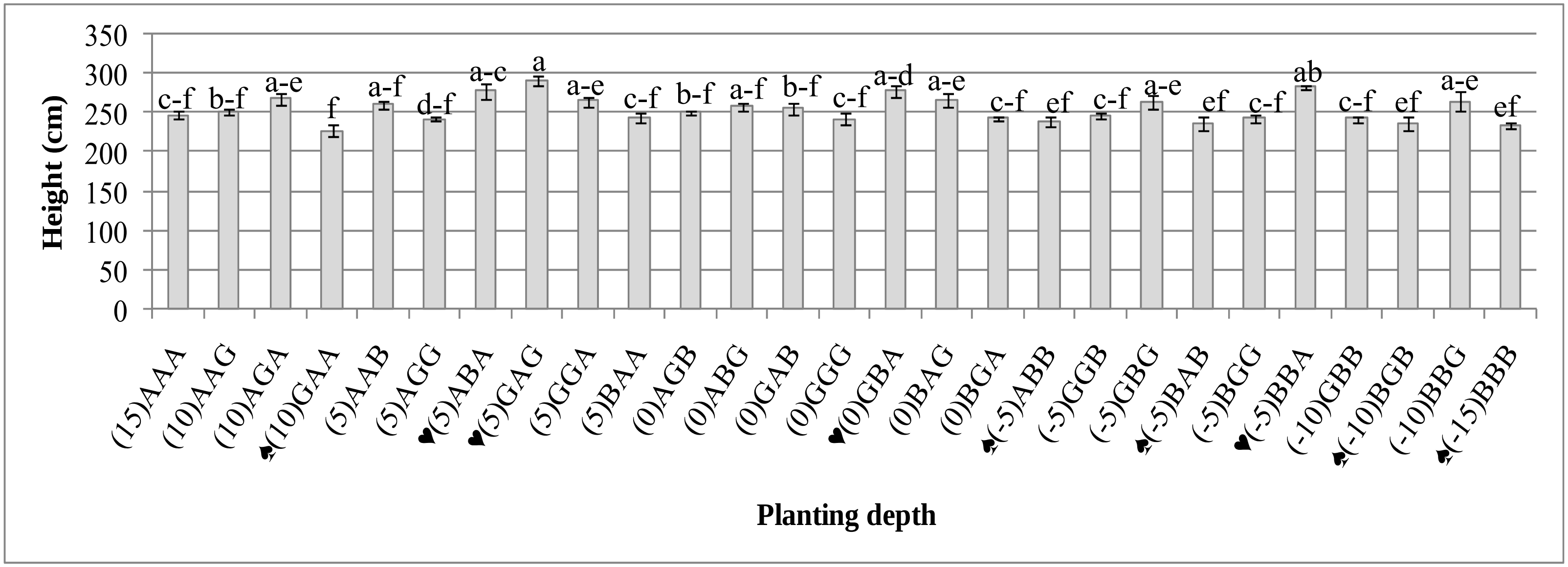

Fig. 4.12. Effect of planting depth on height of lacebark elm (*Ulmus parvifolia* Jacq.) when transplanted to field after 1 year of growth. First letter = 10.8-L depth, second letter = 36.6 L container planting depth, and third letter = field planting depth. See figure 4.2 for clarification. The relation of the original root ball (2.6-L) to existing soil line is presented in brackets (cm). Height was measured from soil line to apex. Means±standard error (n = 6) Levels with same letter are not significantly different according to LSMeans Student's t test, α = 0.05. ♥ Best. ♠ Worst.

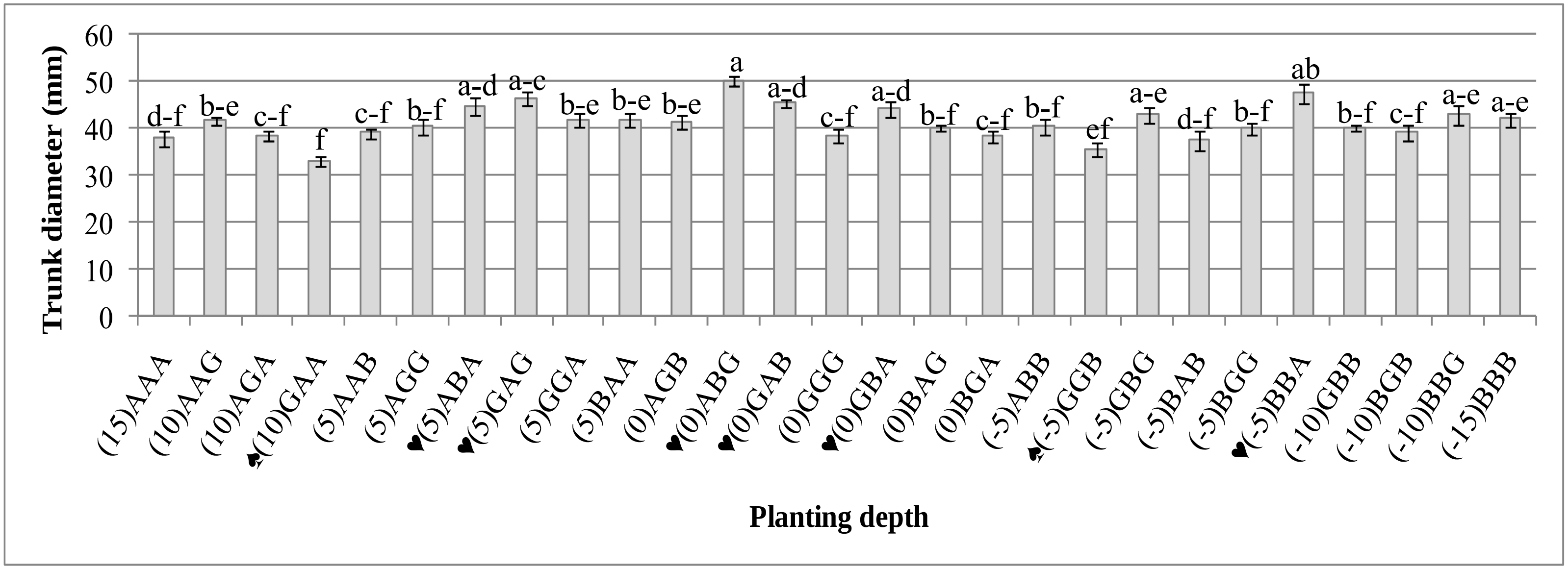

Fig. 4.13. Effect of planting depth on trunk diameter of lacebark elm (*Ulmus parvifolia* Jacq.) when transplanted to field after 1 year of growth. First letter = 10.8-L depth, second letter = 36.6 L container planting depth, and third letter = field planting depth. See figure 4.2 for clarification. The relation of the original root ball (2.6-L) to existing soil line is presented in brackets (cm). Trunk diameter measured approximately 15 cm above existing substrate/soil line. Means±standard error (n = 6). Levels with same letter are not significantly different according to LSMeans Student's t test, α = 0.05. ♥ Best. ♠ Worst.

Discussion

EXPERIMENT 4.1. EFFECT OF PLANTING DEPTH DURING CONTAINER (10.8-L) PRODUCTION

Planting the root collar 5 cm below grade in 10.8-L containers significantly reduced tree height when compared to planting the root collar at soil grade or 5 cm above soil grade. Planting the root collar 5 cm below grade in 10.8-L containers significantly reduced leaf DM, stem DM, and total DM when compared to planting the root collar at soil grade. Planting depth did not significantly affect trunk diameter or root DM. The root mass fraction (total root DM/total DM) indicates that trees planted below grade had a higher investment in roots instead of stems and leaves when compared to trees planted at grade or above grade. Studies have reported similar and contrasting results depending on species. Fare (2005) reported that when bare root dogwood (*Cornus florida* L. 'Cherokee Princess') trees were planted 10.2 or 15.2 cm deep in containers (size not reported) using a pine bark substrate, shoot and root growth was reduced compared to trees planted at depths of 0 and 5.1 cm. However, red maples (*Acer rubrum* L. 'Autumn Flame' and 'Brandywine'), serviceberry (*Amelanchier arborea* x *A. grandiflora* (Mich. F.) Fern.), and zelkova (*Zelkova serrata* (Thunb.) Mak. 'Green Vase') were not affected (height and caliper) by potting depth (Fare, 2005). It was suggested that the pine bark substrate enhanced oxygen flow to the roots, whereas planting deep in landscape settings might be a problem due to decreased oxygen movement (Fare, 2005). In contrast, Giblin et al. (2005) reported that when bare root birch (*Betula platyphylla* var. *japonica* Sukatchev 'Whitespire'), green ash (*Fraxinus pennsylvanica* Marsh.), crabapple (*Malus* Tourn. *ex* L. x 'Spring Snow'), and swamp white oak (*Quercus bicolor* Willd.) trees were planted into #10 containers (manufacturer not reported) in a pot-in-pot system at depths of 0, 5, 10, and 15 cm, root volume decreased with increasing planting depth after 4 months. Green ash and swamp white oak had greater caliper growth at 0 cm depth when compared to the 15 cm depth, while the crabapples and birches were not significantly different (Giblin et al., 2005).

Planting the root collar at soil grade or 5 cm above soil grade significantly reduced leaf chlorophyll concentration (20% or 16%, respectively) when compared to planting the root collar at 5 cm below soil grade. Wells et al. (2006) reported that when planted 31 cm below grade in field, Yoshino cherry (*Prunus* x *yedoensis* Matsum.) and red maple (*Acer rubrum* L.) had significantly lower chlorophyll content as estimated by SPAD meter readings (Wells et al., 2006). This was suggested to have been due to reduced water infiltration to the root ball at depth and insufficient access to shallow mineral nutrient pools (Wells et al., 2006). In our study, containers were placed under shade cloth and were grown in a pine bark substrate, so the reduced chlorophyll in trees at grade or above grade was probably not due to a lack of water or nutrients, but could be due to a dilution effect as the leaves were larger (data not collected).

Planting the root collar 5 cm above soil grade significantly reduced net photosynthetic activity when compared to planting the root collar at soil grade or 5 cm below grade, respectively. Even though trees above grade had equivalent above ground mass, the trees could have had reduced water uptake due to the exposed root-ball, however, stem xylem water potential was lower in trees planted above compared to trees planted at grade, but this affect was not significant.

EXPERIMENT 4.2. EFFECT OF PLANTING DEPTH DURING CONTAINER (36.6-L) PRODUCTION

Trees planted AB had the greatest height, root DM, shoot DM, and total DM when compared to other treatments. The original root ball in the AB treatment is at substrate grade, and there is a 5 cm layer of substrate between the exposed surface and the 10.8-L root ball once transplanted to the 36.6 L container. This could have allowed for adequate oxygen flow to the original root ball as well as moisture retention due to the buffer of media from the exposed surface. Trees planted BB had the greatest trunk diameters while trees planted AA had the lowest trunk diameters. Trees planted BB and AA are at opposite ends of the spectrum in regards to where the original root ball is located in relation to the substrate surface, so the trees planted BB may have been less water stressed than the exposed AA treatments. Thus, while below grade planting was detrimental to tree growth in smaller 10.8-L containers, it appeared beneficial in some cases in larger 36.6-L containers. This may be due to the typical drying that occurs in upper levels of container substrates versus the perched water tables that can occur near the bottom of some containers (Bunt, 1988).

Gilman and Harchick (2008) reported that live oak (*Quercus virginiana* 'SDLN' Cathedral Oak®) trees planted deeply (6.35 cm) into #3 (10.1-L) air root pruning containers (Accelerator®), then deeply (6.35 cm; total 12.7 cm from surface) into #15 (45.4-L) Accelerator® containers, and then deeply (6.35 cm; total 19 cm from surface) into #45 (158.8-L) Accelerator® containers had the most severe root defects (fewer and smaller diameter roots) than those planted deep (1.3, 3.8, 6.4, 8.9, and 11.4 cm) in the #3 containers and maintained at #3 container depth at subsequent transplants. After 40 months, live oaks planted at 3.8 and 8.9 cm depths had significantly greater calipers than those planted 1.3 cm deep, while height was greater for trees planted 1.3 cm deep compared to planting at 6.4, 8.9, 11.4, and 19.0 cm deep (Gilman and Harchick, 2008).

Trees planted BA and AA had significantly reduced total leaf chlorophyll when compared to trees planted GA, BB, AB, and GB. Trees planted AG and AA had significantly reduced net photosynthetic activity compared to trees planted GG and GB, which was similar to what was seen in experiment 4.1. Trees planted AA and BA had significantly less water potential than trees planted GG and GA.

EXPERIMENT 4.3. EFFECT OF PLANTING DEPTH DURING CONTAINER PRODUCTION ON LANDSCAPE ESTABLISHMENT

Planting depth did not significantly affect relative growth rate (RGR) in height or diameter of lacebark elm. Relative growth rate was higher from March 2007 - August 2007 when compared to August 2006 – March 2007 for height and diameter as one would expect as growth slows during the winter and early spring months. Other studies are currently in progress of determining what happens after trees that have been planted too deep during container production and then are transplanted to field conditions (Fare, 2005). Planting depth did not significantly affect total leaf chlorophyll concentration in lacebark elm. In contrast, Wells et al. (2006) reported that when balled-and-burlapped Yoshino cherry (*Prunus* x *yedoensis* Matsum.) were planted with the root flare at 15 cm or 31 cm below grade, Yoshino cherry and red maple had significantly lower chlorophyll content as estimated by SPAD meter readings (Wells et al., 2006). This was suggested to have been due to reduced water infiltration to the root ball at depth and insufficient access to shallow mineral nutrient pools (Wells et al., 2006). The lacebark elm used in this study, although initially affected in container production, may not have been as severely affected once established in field conditions due to its tolerance or ability to avoid injury as a result of low soil oxygen (Pirone, 1972). These responses suggest that in general the best growth in the field was found when root collars were placed at or 5 cm above grade while the worst growth was on treatments 5 to 15 cm below grade or 10 cm or more above grade.

Conclusion

During container production, planting depth affected tree growth. When transplanted in the first experiment, trees overall had better growth when planted at grade, and tended to have reduced growth when planted below grade. In the second experiment, tree growth was variable across planting depths. Trees planted AA tended to have reduced growth when compared to trees planted AB. Once transplanted to the field, planting depth appears to be related more to avoiding extremes of variation above or below the original grade at which seedlings were germinated. The bad news is that what is best relative to planting depth for growth during container production may not be best for landscape establishment. The good news is that it appears to be possible to ameliorate prior planting depth affects in production by adjusting planting depths in the landscape.

CHAPTER V
EFFECT OF PLANTING DEPTH AND IRRIGATION ON GROWTH OF SYCAMORE

Introduction

Variability in planting and transplanting practice of trees is of particular concern as optimum planting depth may vary among species and ecotypes, and success may be dependent on environmental conditions and subsequent cultural practices (Arnold et al., 2005; Ball, 1999; Browne and Tilt, 1992; Drilias et al., 1982; Gilman and Grabosky, 2004; Pirone et al., 1988). Most information on appropriate planting and transplanting practices is anecdotal (Watson and Himelick, 1997) and few experiments have been carried out to test the effect of these practices on tree growth.

Planting trees too deep may cause significant reductions in tree growth. Arnold et al. (2005) suggested that planting the root collar deep in heavier soil may result in poor growth, possibly as a result of decreased soil moisture and/or oxygen. Wells et al. (2006) reported that when balled-and-burlapped Yoshino cherry (*Prunus* x *yedoensis* Matsum.) trees were planted with root flares at 15 cm or 31 cm below grade, a 50% mortality rate was reported 2 years after transplanting, while all trees planted with root flares at grade survived. This was suggested to have been due to reduced water infiltration to the root ball at depth and insufficient access to shallow mineral nutrient pools. Similarly, transplanting container-grown sycamore (*Platanus occidentalis* L.) trees into field conditions (Boonville fine sandy loam) with the root collars 7.6 cm below grade adversely affected survival and growth (Arnold et al., 2007). Planting trees with root collars above grade may also cause significant reductions in tree growth possibly due to a wicking effect from the exposed root ball. However, this may be dependent on other environmental factors such as soil conditions. For example, Arnold et al., (2007) reported that sycamore trees transplanted 7.6 cm above grade had a significantly greater height and trunk diameter when compared to trees transplanted at grade in a heavy soil (Arnold et al., 2007).

During tree transplant establishment, soil water content is presumably a determining factor for plant growth and survival (Gilman, 1990; Kozlowski and Davies, 1975). When live oak (*Quercus virginiana* L.) root zones were maintained at a steady water content compared to high soil water content fluctuations, they tended to have enhanced establishment, growth, and survival in a sandy soil (Gilman et al. 1998). In addition, when live oaks were frequently irrigated after field transplant in sandy soil they grew twice as fast (diameter and height) in the first growing season as trees which were infrequently irrigated (Gilman, 2004). However, positive effects of irrigation on live oak growth rates disappeared in the second season, possibly as a result of full tree establishment (Gilman, 2004). Similarly, red maples (*Acer rubrum* L.) subjected to frequent irrigation after transplanting had greater trunk diameter, increased root number, root diameter, and uniform root distribution, when compared to trees irrigated less frequently (Gilman et al., 2003). Results from the above-mentioned research indicate that irrigation practices including frequency and volume are important to tree survival at transplant. What remains unclear is the effect of planting depth and irrigation interactions on longer term plant growth and survival.

Sycamores are much prized and frequently planted riparian trees, valued for their aesthetic value and contribution to the landscape as fast growing shade and avenue trees in urban and rural environments (Bailey, 1960; Bailey and Bailey, 1976; Liu et al., 2007). It is important to determine not only the effects of planting and transplanting practices on initial tree survival at transplant, but also to assess the longer term effects of these practices. The objective of the following research was to determine the effects of different combinations of planting depths and irrigation treatments on landscape establishment of sycamore trees.

Materials and Methods

CULTURAL CONDITIONS

Sycamore cuttings were collected in September 2004 from stock plants (group of clones from open pollinated siblings) grown under shade (55% light exclusion) in a graveled nursery at Texas A&M University Horticultural Gardens, College Station, TX (lat. 30°37.78'N. long. 96°20.51'W.). Cuttings included the shoot apex and were approximately 9 cm in length. The basal 1 cm of each cutting was dipped in a commercial rooting powder (0.3% indole-3-butryic acid, Hormex No. 3, Brooker Chemical Corp., Chatsworth, CA) and inserted (to approximately 1 cm depth) in 10 cm x 36 cm x 51 cm black, plastic flats (Kadon, Corp., Dayton, OH) containing perlite (Coarse Perlite Premium Grade, Sungro™ Horticulture, Pine Bluff, AR). Cuttings were placed in a greenhouse under intermittent mist (4 s every 10 min from dawn to dusk).

Uniform rooted cuttings were transplanted, after approximately 20 d, into 0.946-L, black, plastic containers (Dillen Products, Middlefield, OH), with their root collars at the substrate (Metro-Mix® 700 Series, SUNGRO®, Bellevue, WA) surface (grade). Root collars were defined as the area where the topmost adventitious roots formed. Transplanted cuttings were transferred into the nursery and maintained under shade (55% light exclusion). Transplanted cuttings were fertigated (0.27 $L{\cdot}min^{-1}$ flow rate) as required with sulfuric acid-injected water (pH 6.3-6.5) containing 50 $mg{\cdot}L^{-1}$ of N from a water soluble fertilizer (Peter Professional® Acid Special water soluble fertilizer, 21N-3.1P-5.8K, Scott's Company, Marysville, OH).

Young trees (liners) (approximately 30 cm in height) were transplanted after 250 d, into 2.6-L (#1) black plastic containers (C-300S Classic, Nursery Supplies, Inc., Chambersburg, PA) and grown for approximately 70 d, after which the trees were transplanted into 6.2-L (#2) black plastic containers (Poly-Tainer™ 2, Nursery Supplies, Inc., Chambersburg, PA). Trees were transplanted with root collars at substrate (composted pine bark mulch; Earth's Finest Black Diamond Mulch, The LetCo Group, Dallas, TX) surface (grade). Container substrate was amended with the following: 7 $kg{\cdot}m^{-3}$ 15N-3.9P-9.9K controlled release fertilizer (Scotts Osmocote®Plus 15-9-12, Scotts-Sierra Horticultural Products Co., Marysville, OH), 4 $kg{\cdot}m^{-3}$ dolomitic limestone (Austin White Lime Company, Austin, TX), 2 $kg{\cdot}m^{-3}$ gypsum (Hoedown™ Standard Gypsum LP, Fredericksburg, TX), and 1 $kg{\cdot}m^{-3}$ micronutrients (Scotts Micromax® micronutrients, Scotts-Sierra Horticultural Products Co., Marysville, OH). Liners and trees were maintained under shade and fertigated as previously described.

Trees (mean height 120.0±0.9 cm, mean trunk diameter 9.5±0.1 mm) were transplanted, after approximately 40 d, into field conditions at the horticulture farm, College Station. Trees were transplanted at various depths in relation to the root collar (grade, 7.6 cm below grade, or 7.6 cm above grade) and watered as required. Trees were staked (1.8 m bamboo stakes; Tonkin Bamboo Cane, Welli Tonkin Bamboo Export Co., Ltd., Shenzhen, China) and tied (Tapener® HT-B2 Max®, Max Co. Ltd., Tokyo, Japan). Approximately 2 weeks after transplanting, trees were irrigated with 0, 1, 2, or 4 spray stakes (SS-AG160LGN-100, Lt. Green Low Flow 160 Spray Pattern, Aboveground Spot-Spitter®, Roberts Irrigation, San Marcos, CA) per tree at an approximate flow rate of 0 $L{\cdot}min^{-1}$ (0x recommended rate), 0.42 $L{\cdot}min^{-1}$ (1/2x recommended rate), 0.84 $L{\cdot}min^{-1}$ (1x recommended rate), and 1.68 $L{\cdot}min^{-1}$ (2x recommended rate), respectively. Trees were pulse-irrigated for 10 min when soil water potential in the 1x treatment reached approximately -15 kPa (Model 2725, JetFill Tensiometers, Soil Moisture Equipment Corp., Santa Barbara, CA). The soil had a textural analysis of 74% sand, 16% silt, and 10% clay (sandy loam), contained 2.13% organic matter (OM), pH 5.0, electrical conductivity (EC) 0.099 $dS{\cdot}m^{-1}$, and had nutrient levels with the following $\mu g{\cdot}g^{-1}$: 12 N, 40 P, 54 K, 277 Ca, 30 Mg, 14 S, 196 Na, 102.3 Fe, 0.51 Zn, 6.19 Mn, 0.28 Cu, and 0.08 B (Soil, Water, and Forage Testing Laboratory, Texas A&M University, College Station, TX).

PLANT GROWTH PARAMETERS

Tree height, from soil line to apical tip (tape measure), and trunk diameter (approximately 15 cm above soil/substrate line) with a digital caliper (Max-Cal "Blade" caliper, Fred V. Fowler Co. Inc., Newton, MA) were measured every 6 months from start (September 2005) to end of the experiment (September 2007). Relative growth rate was calculated as described by Hoffmann and Porter (2002) for height and trunk diameter. Leaf chlorophyll concentration was determined at the end of the experiment by extraction of chlorophyll with acetone (Harborne, 1998). This procedure was modified as follows: five leaf discs (0.3165 cm^2) per tree were collected from representative semi-mature leaves, placed in 5 mL of 80% acetone (Mallinckrodt Lab. Chemicals, Phillipsburg, NJ), and stored in the dark for 7 d at 4 °C. Supernatant was quantified with a spectrophotometer (Beckman Coulter™ Du® Series 640 UV/Vis Spectrophotometer, Beckman Coulter, Inc. Fullertan, CA) at 645 and 663 nm, and compared to an 80% acetone blank standard. Total chlorophyll concentration was expressed as $\mu g \cdot cm^{-2}$.

STATISTICAL DESIGN

The experiment was a randomized complete block design with four irrigation treatments x three transplant depths x ten blocks containing single plant replications per treatment combination. Effects of irrigation and transplant depth on survival, tree height, trunk diameter, and leaf chlorophyll concentration were analyzed using the analysis of variance (ANOVA) procedure in the JMP system for Windows, Release 7.02 (SAS Institute Inc., Cary, NC) with dead trees treated as missing data points.

Results

Tree survival was significantly ($P \leq 0.001$) affected by planting depth, but not irrigation treatment (Table 5.1.). There was no significant planting depth x irrigation treatment interactions. Planting the root collar 7.6 cm below soil grade significantly reduced survival (53% mortality) compared to planting at grade or planting 7.6 cm above grade (0% mortality).

Planting depth and date of measurement had a significant ($P \leq 0.001$) effect on relative growth rate based upon height (RGR_{height}) and diameter ($RGR_{diameter}$) of surviving trees (Table 5.2). There was a significant ($P \leq 0.001$) planting depth x date interaction for both height and relative growth rate. Irrigation treatments did not significantly affect RGR_{height} or $RGR_{diameter}$ at any time.

Table 5.1. Effect of planting depth and irrigation treatment on survival of sycamore (*Platanus occidentalis* L.) 2 years after transplant to the field.

Depth[z]	Irrigation[y] ($L \cdot min^{-1}$)	Survival (%)
Above	0	100±0.0[x]
	0.42	100±0.0
	0.84	100±0.0
	1.68	100±0.0
Grade	0	100±0.0
	0.42	100±0.0
	0.84	100±0.0
	1.68	100±0.0
Below	0	50±16.7
	0.42	50±16.7
	0.84	40±16.3
	1.68	50±16.7
Significance[w]		
Depth		<0.001
Irrigation		0.965
Depth x Irrigation		0.997

[z]Root collars planted 7.6 cm above soil grade (Above), at grade (Grade), or 7.6 cm below grade (Below).
[y]Trees were pulse irrigated with spray stakes (0, 1, 2, or 4 spray stakes per tree delivering 0.42 $L \cdot min^{-1}$ per stake) for 10 minutes as required (when soil water potential reached approximately -15 kPa).
[x]Mean±standard error (n=10).
[w]Significance according to ANOVA. *P*-values presented.

Averaged across irrigation treatment, RGR_{height} was greatest from March 2006-September 2006, and significantly decreased in the following order: March 2007-September 2007, and was lowest from September 2005-March 2006 and September 2006-March 2007 (Table 5.3). On average planting trees with root collars 7.6 cm below soil grade significantly reduced RGR_{height} (34% or 27%) when compared to planting trees with root collars at grade or 7.6 cm above grade, respectively. The negative effect of deep planting on RGR_{height} was stronger during the March 2006 – September 2006 growth period than during the other growth periods where planting depth effects were small ($P_{\text{time x depth}} \leq 0.001$, Table 5.3).

Averaged across season and depth, $RGR_{diameter}$ was greatest from March 2006-September 2006, and significantly decreased in the following order: March 2007-September 2007, and was lowest from September 2005-March 2006 and September 2006-March 2007 (Table 5.4). On average planting trees with root collars 7.6 cm below soil grade significantly reduced $RGR_{diameter}$ (39% or 34%) when compared to planting trees with root collars at grade or 7.6 cm above grade, respectively.

Table 5.2. Fixed effects test significance of relative growth rate for height and trunk diameter (RGR_{height} and $RGR_{diameter}$) of sycamore (*Platanus occidentalis* L.).

Fixed effects test	RGR_{height}[z]	$RGR_{diameter}$[y]
Depth[x]	<0.001[w]	<0.001
Irrigation[v]	0.928	0.925
Depth x Irrigation	0.993	0.949
Date[u]	<0.001	<0.001
Date x Irrigation	0.986	0.909
Date x Depth	<0.001	<0.001
Date x Irrigation x Depth	0.586	0.926

[z]Relative growth rate (RGR) calculated according to Hoffmann and Porter (2002). Height measured from soil line to apex of tree.

[y]Trunk diameter measured 15.2 cm above soil/substrate line.

[x]Root balls planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).

[w]*P*-values.

[v]Trees were pulse irrigated with spray stakes (0, 1, 2, or 4 spray stakes per tree delivering 0.42 $L \cdot min^{-1}$ per stake) for 10 minutes as required (when soil water potential reached approximately -15 kPa).

[u]Dates that trees were measured: September 2005, March 2006, September 2006, March 2007, September 2007.

Final tree height was not significantly affected by planting depth (P =0.072), irrigation (P =0.895), and there was no significant planting depth x irrigation interaction (P =0.654) (data not shown). Final trunk diameter was significantly (P =0.003) affected by planting depth (Fig. 5.1), but not irrigation treatment (P =0.348), and there was no significant interaction (P =0.725). Planting trees with root collars at grade significantly increased (9%, 14%) final trunk diameters when compared to planting trees with root collars above grade or below grade, respectively.

Table 5.3. Effect of planting depth and irrigation treatment on relative growth rate on tree height (RGR_{height}) of surviving sycamore (*Platanus occidentalis* L.).

Depth[z]	$RGR_{height}{}^{x}$ ($\mu m \cdot mm^{-1} \cdot day^{-1}$)			
	September 2005-March 2006	March 2006-September 2006	September 2006-March 2007	March 2007-September 2007
Above	0.07±0.10	4.43±0.12	-0.31±0.02	3.09±0.07
Grade	0.08±0.10	5.07±0.14	-0.24±0.02	3.16±0.06
Below	-0.06±0.05	2.18±0.40	-0.23±0.02	3.39±0.23

[z]Root collars planted 7.6 cm above soil grade (Above), at grade (Grade), or 7.6 cm below grade (Below).
[x]Relative Growth Rate (RGR) calculated according to Hoffmann and Porter (2002). Height measured from soil line to apex of tree.
[w]Means±standard error (n=10, excluding dead trees).

Table 5.4. Effect of planting depth and irrigation treatment on relative growth rate in trunk diameter ($RGR_{diameter}$) of surviving sycamore (*Platanus occidentalis* L.).

Depth[z]	$RGR_{diameter}{}^{y}$ ($\mu m \cdot mm^{-1} \cdot day^{-1}$)			
	September 2005-March 2006	March 2006-September 2006	September 2006-March 2007	March 2007-September 2007
Above	0.88±0.07	5.55±0.13	0.58±0.06	3.27±0.09
Grade	1.13±0.10	6.16±013	0.62±0.05	3.20±0.07
Below	-0.03±0.11	2.94±0.52	0.53±0.07	3.29±0.18

[z]Root collars planted 7.6 cm above soil grade (Above), at grade (Grade), or 7.6 cm below grade (Below).
[y]Relative Growth Rate (RGR) calculated according to Hoffmann and Porter (2002). Trunk diameter measured 15 cm above soil/substrate line.
[x]Means±standard error (n=10, excluding dead trees).

Total leaf chlorophyll concentration was not significantly affected by planting depth (P = 0.474) or irrigation treatment (P = 0.546), and there was no significant planting depth x irrigation treatment interaction (P = 0.327) (data not shown).

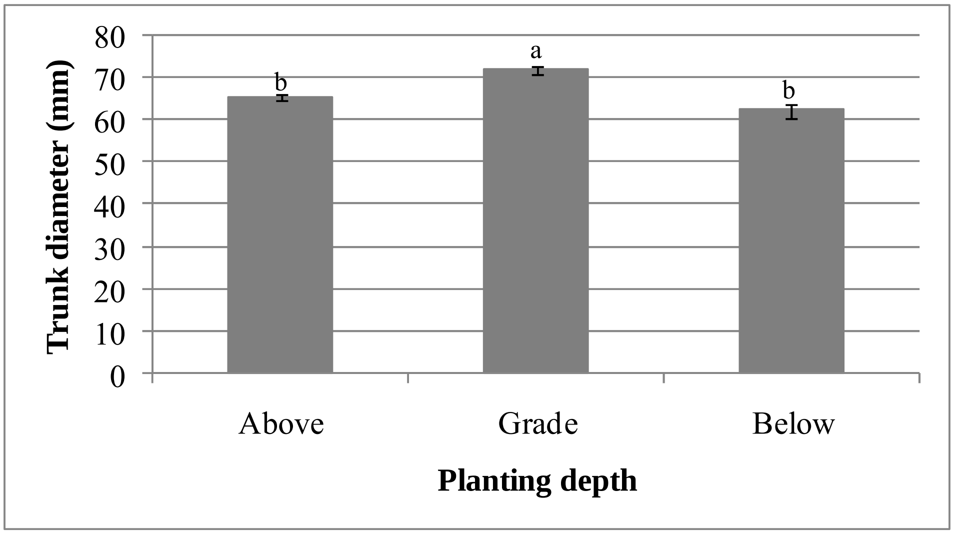

Fig. 5.1. Effect of planting depth on final trunk diameter in surviving sycamore (*Platanus occidentalis* L.). Root collars planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below). Trunk diameter measured 15 cm above soil/substrate line. Means±standard error (n=10, excluding dead trees). Significance using ANOVA (P = 0.003). Levels with the same letter are not significantly different according to LSMeans Student's t test, $\alpha = 0.05$.

Discussion

Sycamore survival and growth was significantly affected by planting depth, but not by irrigation treatment. In our study sycamore growth was not significantly affected by irrigation treatment possibly due to wetter than normal conditions during the growing season, as temperature did not deviate much from the normal averages (Table 5.5). Average RGR_{height} and $RGR_{diameter}$ were greater for the 2006 growing season than for the 2007 growing season. It is unlikely that excessive temperatures would explain the difference in growth between years. The 2006 growing season was on average 0.8°C warmer than average, while the 2007 season was only 0.06°C warmer than average (Table 5.5). In both years, the trees experienced wetter than normal conditions during the June and July months, when drought conditions are normally most likely to occur (Table 5.5). Total precipitation during the peak growing season (March-September) in 2006 was

24 mm above average (Table 5.5) and was 77 mm above average in 2007. It is likely that excessive amounts of water during the growing season in 2007 reduced oxygen availability to the plants and produced anoxic conditions that slowed down plant growth, but it did not stop plant growth altogether. Coleman (2007) suggested that sycamore have a high nutrient and water demand, and thus may have smaller diameter roots and higher root length density, which may make sycamore more responsive/adaptable to resource availability and/or stress. In addition, Tang and Kozlowski (1982) reported that sycamore seedlings can initiate and grow adventitious roots from the original root system and/or submerged portion of the stem in response to root mortality under anaerobic conditions. This may not be the case for all tree species.

Planting depth significantly affected sycamore growth. Planting the root collar below grade resulted in increased tree mortality and also reduced tree height and trunk diameter when compared to planting root collars at grade or 7.6 cm above grade (from those surviving). Wells et al. (2006) suggested that when Yoshino cherry (*Prunus* x *yedoensis* Matsum.) trees were planted with their root collars below grade they experienced reduced water infiltration and insufficient access to shallow mineral nutrient pools, causing nutrient deficiencies and increasing tree mortality. Arnold et al. (2005) suggested that in heavier soil, planting the root collar deep may result in poor growth, possibly as a result of decreased soil moisture and/or oxygen. Planting deeply in heavy soils can cause the roots to experience prolonged flooding conditions after a period of heavy rainfall, resulting in anoxic conditions. During drought periods, trees planted deeply in heavy soils will have more problems extracting water from the soils as heavy soils tend to have smaller pore spaces and a greater amount of plant unavailable water. Kozlowski and Pallardy (1997) reported that stomata in sycamore readily close under anaerobic soil conditions resulting in reduced respiration and subsequent growth. However, Tang and Kozlowski (1982) and Tsukahara and Kozlowski (1985) observed the formation of swollen lenticels on the stems of sycamore seedlings in response to anaerobic conditions, which may enhance absorption and translocation of oxygen to the roots. Thus, sycamore trees may be able to adapt to periodically flooded soils. Arnold et al. (2007) reported that planting sycamore with root collars 7.6 cm below grade resulted in 50% mortality when planted in a fine sandy loam which was underlain at a depth of 15 to 30 cm with a hard clay pan. In the present study, planting young trees with their root collars below grade may have caused the roots to suffer periods of anoxic conditions interspersed with periods of drought while the root system was not developed yet, resulting in 53% mortality within 12 months, even in the sandy loam at this study site. However, given the general lack of an irrigation effect in this study, the growth response to planting depth during the first year was likely due to factors other than soil moisture.

Conclusion

Sycamore survival and growth was significantly affected by planting depth, but not by irrigation treatment. Planting the root collars 7.6 cm below grade resulted in 53% tree mortality by the end of the first year, while trees planted with root collars at grade or 7.6 cm above grade had 0% mortality. Planting the trees with root collars at grade or above grade in a sandy loam soil produced taller trees with larger trunk diameters compared to trees planted below grade. A lack of interaction for growth and survival among planting depths and irrigation levels suggests that planting depth responses in sycamore were due to factors other than soil moisture levels.

Table 5.5. Reported monthly temperature and precipitation departures[z] for the duration of the study.

Year	Month	Temperature departure[y] (°C)	Precipitation departure (mm)
2005	September	2.9	-99
	October	0.6	-53
	November	2.1	94
	December	-0.6	-57
2006	January	3.9	-18
	February	-0.8	34
	March	1.8	50
	April	2.8	-19
	May	0.8	-61
	June	0.1	-11
	July	-0.5	100
	August	0.7	-4
	September	-0.1	-31
	October	0.0	220
	November	0.8	-65
	December	0.9	34
2007	January	-1.7	42
	February	-0.7	-58
	March	2.1	99
	April	-1.6	-8
	May	0.1	-26
	June	-0.1	31
	July	-1.6	68
	August	0.4	-31
	September	1.1	-56

[z]Source: Office of the Texas State Climatologist, Department of Atmospheric Sciences, Texas A&M University, College Station, TX.

[y]Departure of the daily mean temperature was calculated from the average of the maximum and minimum temperatures from the 1971-2000 normals (Office of the Texas State Climatologist). Highlighted areas represent active growing season.

CHAPTER VI
EFFECT OF PLANTING DEPTH AND SEASONAL TRANSPLANT ON GROWTH OF BALDCYPRESS

Introduction

The season in which trees are transplanted may affect plant growth, survival and landscape establishment. It has been suggested that in most temperate locations, transplanting in spring or autumn provides ideal climatic and soil conditions, as root growth is better when the soil is warm and moist, and trees have not started actively growing (Richardson-Calfee and Harris, 2005). However, planting/transplanting in autumn could result in low survival as a result of low physiological potential for root regeneration at this time of year (Larson, 1984) and/or due to the inability of roots to grow at relatively cool soil temperatures (Jenkinson, 1980), which may vary in severity depending on geographic location. Alternatively, transplanting in spring when trees are starting to actively grow may result in excessive carbohydrate drain from the roots (Dumbroff and Webb, 1978).

Successful landscape establishment of trees is also dependent on numerous cultural practices including planting/transplanting depth in relation to the root collar (Arnold et al., 2007; Gilman and Grabosky, 2004). Planting depth in relation to the root collar is of particular concern as it seems to cause tree failure in some species depending on environmental conditions and/or cultural practices (Watson and Hewitt, 2006; Kozlowski and Davies, 1975; Arnold et al., 2007). A lack of water, oxygen, and/or nutrient availability have all been suggested as a reason for tree failure and/or reduced growth (Arnold et al., 2005; Wells et al., 2006). Some trees have been reported to be more susceptible to planting/transplanting seasons and planting depth than others (Arnold et al., 2007; Harris et al., 2001; Richardson-Calfee et al., 2007; Shoemake and Arnold, 1997).

Baldcypress (*Taxodium distichum* (L.) L. Rich.) is a majestic tree of considerable ornamental value in urban and riparian environments (Bailey and Bailey, 1976; Simpson, 1988), and they are widely used in landscapes in the Southern US. Baldcypress is known to tolerate a wide range of soil moisture conditions, ranging from periodic flooding to mild drought (Elcan and Pezeshki, 2002). This research was conducted to determine the effects of different planting depths and planting seasons on landscape establishment of baldcypress, so that we can improve its chances for successful establishment. We hypothesize that baldcypress will have greater growth when transplanted with root collars at soil grade, compared to planting root collars below soil grade or planting root collars above soil grade. We also hypothesize that trees transplanted in autumn will establish and grow faster than those trees transplanted in spring, as soils in Texas stay relatively warm during the winter, trees would have more time to establish a root system before summer drought periods, and carbohydrate drain from the root system would be less likely.

Materials and Methods

CULTURAL CONDITIONS

Baldcypress seeds were collected in Poteet, Texas (lat. $29^{o}0.807$'N. long. $98^{o}34.614$'W) and stored under ambient conditions until required (approximately 2 months). Seeds were immersed in a heated (43°C, 110°F) water bath (180 Series Water Bath, Precision Scientific Inc., Chicago, IL), left to soak for approximately 24 h in the cooling water (to approximately 23 °C), and then rinsed in reverse osmosis (RO) water. This procedure was repeated five times. Seeds were then stratified in a cold room (1.67 °C; Bally Case and Cooler, Inc., Bally, PA) for 90 d in moist peat (Premier® Pro Moss® TBK Professional, Premier Horticulture Inc., Red Hill, PA), and then planted in 10 cm x 36 cm x 51 cm black plastic flats (Dyna-flat™, Kadon Corp., Dayton, OH) containing vermiculite (Sunshine® Strong-Lite® Medium Vermiculite Premium Grade, SUN GRO™ Horticulture, Pine Bluff, AR) and placed in a greenhouse at Texas A&M

University Horticultural Gardens, College Station, TX (lat. 30°37.78'N. long. 96°20.51'W.). Emerging seedlings were irrigated with RO water as required.

Uniform seedlings (approximately 11 cm in height) were transplanted, after approximately 100 d, into 0.85-L black plastic containers (Kinney Bonded Warehouse, Inc., Donna, TX) with their root collars at substrate surface (grade) (Metro-Mix® 700 Series, SUNGRO®, Bellevue, WA). Transplanted seedlings were maintained under shade (55% light exclusion) in a graveled nursery at Texas A&M University Horticultural Gardens, College Station, TX. Plants were fertigated (0.27 $L \cdot min^{-1}$ flow rate) as required with sulfuric acid-injected water (pH 6.3-6.5) containing 50 $mg \cdot L^{-1}$ of N from a water soluble fertilizer (Peter Professional® Acid Special water soluble fertilizer, 21N-3.1P-5.8K, Scott's Company, Marysville, OH).

Young trees (liners) were transplanted, after approximately 80 d, into 2.6-L (#1) black plastic containers (C-300S Classic, Nursery Supplies, Inc., Chambersburg, PA) with their root collars at the substrate (composted pine bark mulch; Landscapers Pride®, New Waverly, TX) surface (grade). Container substrate was amended with the following: 7 $kg \cdot m^{-3}$ 15N-3.9P-9.9K controlled release fertilizer (Scotts Osmocote®Plus 15-9-12, Scotts-Sierra Horticultural Products Co., Marysville, OH), 4 $kg \cdot m^{-3}$ dolomitic limestone (Austin White Lime Company, Austin, TX), 2 $kg \cdot m^{-3}$ gypsum (Hoedown™ Standard Gypsum LP, Fredericksburg, TX), and 1 $kg \cdot m^{-3}$ micronutrients (Scotts Micromax® micronutrients, Scotts-Sierra Horticultural Products Co., Marysville, OH). Liners were maintained in the nursery under shade and fertigated as previously described.

Trees were transplanted, after approximately 225 d, into 10.8-L (#3) black plastic containers (1200C Classic, Nursery Supplies, Inc., Chambersburg, PA) with their root collars at substrate (composted pine bark mulch; Earth's Finest Black Diamond Mulch, The LetCo Group, Dallas, TX) surface (grade). Container substrate was amended as described previously. Trees were maintained in the nursery under shade and fertigated as previously described. Trees were staked (1.2 m bamboo stakes; Tonkin Bamboo Cane, Welli Tonkin Bamboo Export Co., Ltd., Shenzhen, China) and tied (Tapener® HT-B2 Max®, Max Co. Ltd., Tokyo, Japan).

Trees were transplanted to the Horticulture Farm, College Station, TX, after approximately 210 d (19 November 2005) for the autumn transplant and 320 d (12 March 2006) for the spring transplant. Trees were transplanted at various depths in relation to the root collar, at grade (at soil surface), 7.6 cm below grade, or 7.6 cm above grade. Trees were drip-irrigated (T-Tape®, T-Systems Intl. Inc., San Diego, CA) as required. Field soil had a textural analysis of 74% sand, 16% silt, and 10% clay (sandy loam), contained 2.73% organic matter (OM), pH 6.4, electrical conductivity (EC) 0.201 $dS \cdot m^{-1}$, and had nutrient levels with the following $\mu g \cdot g^{-1}$: 11 N, 47 P, 70 K, 490 Ca, 47 Mg, 17 S, 294 Na, 87.4 Fe, 0.87 Zn, 8.69 Mn, 0.28 Cu, and 0.15 B (Soil, Water, and Forage Testing Laboratory, Texas A&M University, College Station, TX).

ASSESSMENT OF PLANT GROWTH

Tree height, from soil line to apical tip, and trunk diameter (15 cm above soil/substrate surface) were measured every four months from the start to the end of the experiment (24 months). Relative growth rate was calculated as described by Hoffmann and Porter (2002) for height and trunk diameter.

STATISTICAL DESIGN

The experiment was a randomized complete block design with three transplant depths x two transplant seasons x ten blocks. There was one tree per treatment combination per block (6 trees per block). Data was analyzed using analysis of variance (ANOVA) in the JMP system for Windows, Release 7.02 (SAS Institute Inc., Cary, NC). The number of observations on each date was: plant height and trunk diameter ($n = 10$).

Results

Planting depth and date that trees were measured significantly affected the relative growth rate in height (RGR_{height}) and diameter ($RGR_{diameter}$) (Table 6.1). There was a significant ($P \leq 0.001$) date x depth interaction. Planting season did not significantly affect RGR_{height} or $RGR_{diameter}$. Survival was 100% across treatments.

Table 6.1. Fixed effects test significance on relative growth rate on height and trunk diameter (RGR_{height} and $RGR_{diameter}$) of baldcypress (*Taxodium distichum* L. (L.) Rich.) using the analysis of variance (ANOVA) method..

Fixed effects test	RGR_{height} [z]	$RGR_{diameter}$ [y]
Depth[x]	<0.001[w]	<0.001
Season[v]	0.432	0.225
Depth x Season	0.7669	0.579
Date[u]	<0.001	<0.001
Date x Season	0.685	0.873
Date x Depth	<0.001	<0.001
Date x Season x Depth	0.718	0.304

[z]Relative growth rate (RGR) calculated according to Hoffmann and Porter (2002). Height measured from soil line to apex of tree.
[y]Trunk diameter measured 15 cm above soil/substrate line.
[x]Root balls planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).
[w]*P*-values.
[v]Trees were either transplanted in the autumn 2005 or the spring 2006.
[u]Dates that trees were measured: March 2006, July 2006, November 2006, March 2007, July 2007, November 2007.

Averaged across season, RGR_{height} was greatest from March 2006-July 2006, and significantly decreased in the following order: March 2007-July 2007, July 2006-November 2006, July 2007-November 2007, and was lowest from November 2007-March 2007 (Table 6.2). Most growth occurred in spring and early summer. On average planting trees with root collars 7.6 cm above soil grade significantly reduced RGR_{height} (24% or 17%) when compared to planting trees with root collars 7.6 cm below grade or at grade, respectively.

Averaged across season and depth, $RGR_{diameter}$ was greatest from March 2006-July 2006, and significantly decreased in the following order: March 2007-July 2007,

Table 6.2. Effect of planting depth on relative growth rate in tree height (RGR_{height}) of baldcypress (*Taxodium distichum* (L.) L. Rich.).

Depth[z]	RGR_{height}[y] ($\mu m \cdot mm^{-1} \cdot day^{-1}$)				
	March 2006 – July 2006	July 2006 – November 2006	November 2006 - March 2007	March 2007 – July 2007	July 2007 – November 2007
Above	2.04±0.15	0.99±0.16	0.11±0.06	2.34±0.09	0.34±0.10
Grade	2.98±0.18	1.19±0.11	0.03±0.05	2.37±0.12	0.44±0.10
Below	3.36±0.14	1.36±0.10	-0.02±0.03	2.49±0.12	0.47±0.08

[z]Root balls planted 7.6 cm above soil grade (Above), at grade (Grade), or 7.6 cm below grade (Below).
[y]Relative growth rate (RGR) calculated according to Hoffmann and Porter (2002). Height measured from soil line to apex of tree.
[x]Means±standard error (n = 10).

Table 6.3. Effect of planting depth on relative growth rate in trunk diameter ($RGR_{diameter}$) of baldcypress (*Taxodium distichum* (L.) L. Rich).

Depth[z]	$RGR_{diameter}$[y] ($\mu m \cdot mm^{-1} \cdot day^{-1}$)				
	March 2006 – July 2006	July 2006 – November 2006	November 2006 - March 2007	March 2007 – July 2007	July 2007 – November 2007
Above	3.76±0.16	1.26±0.11	-0.02±0.08	2.73±0.17	0.11±0.08
Grade	5.02±0.22	1.60±0.12	0.00±0.04	3.01±0.15	0.07±0.08
Below	5.59±0.12	1.82±0.15	0.03±0.08	2.88±0.14	0.01±0.09

[z]Root balls planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below).
[y]Relative growth rate (RGR) calculated according to Hoffmann and Porter (2002). Trunk diameter measured 15 cm above soil/substrate line.
[x]Means±standard error (n=10).

July 2006-November 2006, and was lowest from July 2007-November 2007 and November 2007-March 2007 (Table 6.3). On average planting trees with root collars 7.6 cm above soil grade significantly reduced $RGR_{diameter}$ (24% or 19%) when compared to planting trees with root collars 7.6 cm below grade or at grade, respectively.

Planting depth and transplant season did not significantly (P = 0.081, P = 0.468, respectively) affect final tree height, and there was no significant planting depth x transplant season interaction (P = 0.213) (data not shown). Planting depth significantly ($P \leq 0.001$) affected final trunk diameter (Fig. 6.1), but transplant season did not significantly affect trunk diameter and there was no significant planting depth x transplant season interaction (P = 0.827) (data not shown). Planting trees with root collars below grade or at grade significantly increased final trunk diameter when compared to planting trees with root collars above grade.

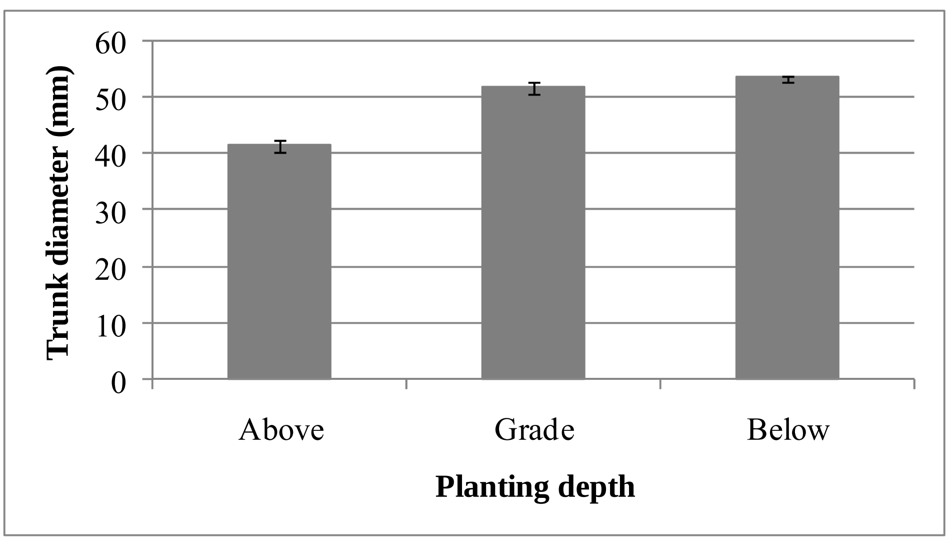

Fig. 6.1. Effect of planting depth on trunk diameter of baldcypress (*Taxodium distichum* (L.) L. Rich.). Root balls planted 7.6 cm above soil grade (above), at grade (grade), or 7.6 cm below grade (below). Means±standard error (n = 10).

Discussion

In this study, planting depth affected RGR_{height} and $RGR_{diameter}$ in baldcypress. Arnold et al. (2007) reported that planting with the root collar 7.6 cm below grade adversely affected the growth of crapemyrtle (*Lagerstroemia indica* L. x *Lagerstroemia fauriei* Koehne.'Basham's Party Pink'), green ash (*Fraxinus pennsylvanica* Marsh.), oleander (*Nerium oleander* L. 'Cranberry Cooler'), sycamore (*Platanus occidentalis* L.), and vitex (*Vitex agnus-castus* L. 'LeCompte'), although the severity varied depending on species. Planting above grade was beneficial for sycamores when compared to planting at or below soil surface grade (Arnold et al., 2007). Contrary to findings by Arnold et al. (2007), where trees planted at grade or above grade outperformed trees planted below grade, baldcypress performed better when planted with their root collars at grade or below grade in this study. Baldcypress is reported to be tolerant to low oxygen/anaerobic soil conditions (Kozlowski and Davies, 1975), which may explain why baldcypress was not negatively affected by planting the root collars below grade. Furthermore, the field soil at the site was a well drained sandy loam, which may have provided ample aeration for trees planted with their root collars at grade or below grade, whereas the soil in the Arnold et al. (2007) study was a fine sandy loam which was underlain by a hard clay pan at 15 to 30 cm depth. Planting baldcypress with root collars above grade in the present study was detrimental to their overall growth. Planting root collars above grade may have resulted in a wicking effect on the exposed portion of the root ball, resulting in root desiccation and thus a reduction in overall tree growth.

Transplanting season did not affect baldcypress RGR_{height} or $RGR_{diameter}$. We suggest that this may have been a result of an unusually wet spring/summer in 2006 and that winters are fairly mild in the Southern U.S. Richardson-Calfee et al. (2007) reported that with proper maintenance of soil moisture, fall and spring transplanting resulted in similar root regeneration as summer planting/transplanting of sugar maple (*Acer saccharum* Marsh.) (Virginia site). In addition, Harris et al. (2001) reported that, with proper irrigation, fall or spring planting/transplanting resulted in similar growth (height and diameter) and rate of root length accumulation in Turkish hazelnut (*Corylus colurna* L.) (Virginia site). In contrast, Shoemake and Arnold (1997) reported that fall transplanting resulted in better growth and survival of sycamore (*Platanus occidentalis* L.) than spring transplanting, which in turn was better than summer transplanting (Central Texas site). Low survival of autumn transplanted seedlings has been reported to be related to a low physiological potential for root regeneration at that time of year (Larson, 1984) (Ohio site) and the inability of new transplants to grow roots in cold soils (Jenkinson, 1980) (Western Sierra Nevada site). However, these varied and contrasting results may depend on plant species/ecotype and/or geographic factors, including climate.

Conclusion

Relative growth rate of height and trunk diameter of baldcypress was significantly affected by planting depth. Planting the trees with root collars at soil grade or slightly below soil grade (7.6 cm) in a sandy loam soil produced taller trees with larger stem diameters than planting root collars slightly above soil grade (7.6 cm). We suggest that the difference between our finding and the literature may be a result of species variation. Plant species and cultivars within species can differ markedly in their response to environmental/cultural stresses. In that, each tree species originating from a specific environment may represent an ecotype adapted to that particular environment. Therefore, tree survival and performance may depend on the difference between the environment from which the tree was obtained and the experimental system/landscape site into which it was introduced. Baldcypress is naturally found on sites that frequently flood and thus maybe less affected by hypoxia or anoxia than other species, perhaps explaining its tolerance to below grade planting on this sandy soil.

CHAPTER VII
CONCLUSION

Trees have environmental, economic, cultural, and aesthetic landscape value (Perkins and Heynen, 2004; Summit and Sommer, 1998). The inability to adequately quantify the effects of inappropriate tree planting and transplanting practices threatens the long-term viability and productivity (sustainability) of trees within terrestrial ecosystems. Planting and transplanting practices vary substantially among firms and individual practitioners (arborists, foresters, horticulturists, and other professionals) (TCIA, 2005; Watson and Himelick, 1997). Variability in planting depth is of particular concern, specifically the location of the root collar relative to soil grade, as optimum planting depth may vary among species, and may be dependent on cultural practices and/or environmental conditions (Arnold et al., 2005; Ball, 1999; Browne and Tilt, 1992; Drilias et al., 1982; Gilman and Grabosky, 2004; Pirone et al., 1988). In spite of all the research that already has been conducted on the effects of soil and environmental parameters such as soil type, soil bulk density, soil water content and soil temperature on above and belowground tree performance, comparatively little is known about the interactions between these parameters and transplanting practices. In the preceding chapters we explored the effect of planting depth on tree growth, development, and landscape establishment/survival under different cultural practices, including soil amendment, container production, irrigation, and season.

In chapters II and III we studied the effect of planting depth and soil amendment on live oak and baldcypress, respectively. Overall, live oak tree growth was variable with trends from this preliminary research indicating that live oak trees under these study conditions had better growth when planted at grade in sand in raised beds as indicated by $RGR_{diameter}$ and root and shoot visual ratings. This preliminary study provided insight for a future study including using plant material propagated on site to ensure that the original root collar of seedlings was known, and extending the duration of the study. Similarly planting baldcypress trees in the incorporated sand and sand in raised bed sections resulted in trees with greater RGR_{height}, $RGR_{diameter}$, total fine root length, fine root dry mass, and shoot DM. Trees planted above grade had decreased RGR_{height}, coarse roots, and a greater incidence of potentially girdling roots when compared to trees planted at or below grade. Planting trees at soil grade resulted in trees with greater shoot DM, reduced mortality, and less negative stem water potentials when compared to trees planted below grade. Although varying in severity, adverse effects of below grade planting were present across soil types, the severity of adverse effects of below grade planting was greatest in the higher clay content control soil than in raised beds with sandy soils.

In chapter IV we explored the effect of planting depth during container production and subsequent landscape establishment of lacebark elm. During container production, planting depth affected lacebark elm tree growth. When transplanted in the first experiment, trees overall had better growth when planted at grade, and tended to have reduced growth when planted below grade. In the second experiment, tree growth was variable across planting depths. Trees planted above and then above tended to have reduced growth when compared to trees planted above and then below. Once transplanted to the field, planting depth appears to be related more to avoiding extremes of variation above or below the original grade at which seedlings were germinated. The bad news is that what is best relative to planting depth for growth during container production may not be best for landscape establishment. The good news is that it appears to be possible to ameliorate prior planting depth affects in production by adjusting planting depths in the landscape.

In chapter V we examined the effect of planting depth and irrigation practices on growth and landscape establishment of sycamore. Sycamore survival and growth was significantly affected by planting depth, but not by irrigation treatment. Planting the root collars 7.6 cm below grade resulted in 53% tree mortality by the end of the first year, while trees planted with root collars at grade or 7.6 cm above grade had 0% mortality. Planting the trees with root collars at grade or above grade in a sandy loam soil produced taller trees with larger trunk diameters compared to trees planted below grade. A lack of interaction for growth and survival among planting depths and irrigation levels suggests that planting depth responses in sycamore were due to factors other than soil moisture levels.

In chapter VI we looked at the effect of planting depth and transplant season on the growth and landscape establishment of baldcypress. Relative growth rate of height and trunk diameter of baldcypress was significantly affected by planting depth. Planting the trees with root collars at soil grade or slightly below soil grade (7.6 cm) in a sandy loam soil produced taller trees with larger stem diameters than planting root collars slightly above soil grade (7.6 cm). We suggest that the difference between our finding and the literature may be a result of species variation. Plant species and cultivars within species can differ markedly in their response to environmental/cultural stresses. In that, each tree species originating from a specific environment may represent an ecotype adapted to that particular environment. Therefore, tree survival and performance may depend on the difference between the environment from which the tree was obtained and the experimental system/landscape site into which it was introduced. Baldcypress is naturally found on sites that frequently flood and thus maybe less affected by hypoxia or anoxia than other species, perhaps explaining its tolerance to below grade planting on a very well drained sandy soil.

In conclusion tree planting depth is of particular concern for tree growth, development, and performance in the landscape, as optimum planting depth varied among species used in this study, and was also dependent on cultural practices and/or environmental conditions including soil amendment and container production. Although, irrigation treatments did not affect sycamore growth and performance, and planting season did not affect the growth and performance of baldcypress, we suggest that this may not always be the case with other plant species. Furthermore, it is important to note that plant species and cultivars within species may differ markedly in their response to environmental/cultural stresses, including planting depth. Each tree species originating from a specific environment may represent an ecotype adapted to that particular environment. Therefore, tree survival and performance may depend on the difference between the environment from which the tree was grown and the experimental system or landscape site into which it is introduced.

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APPENDIX

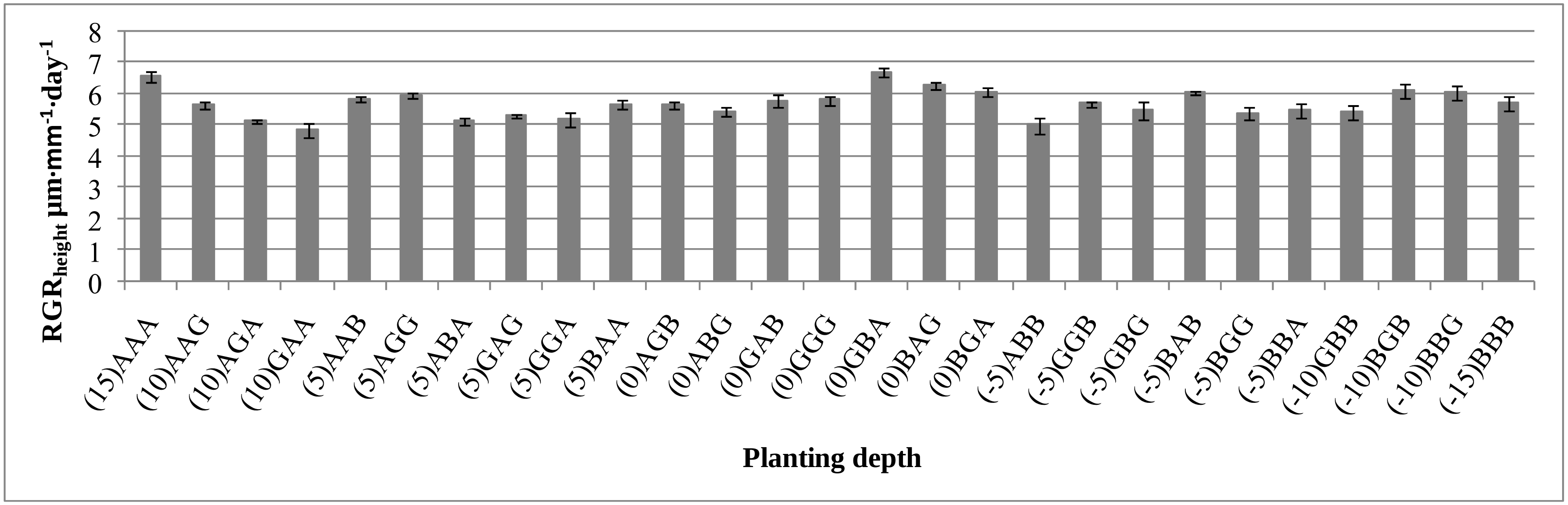

Fig. A.1. Effect of planting depth on relative growth rate in height (RGR$_{height}$) from March 2007-August 2007 of lacebark elm (*Ulmus parvifolia*) when initially transplanted (10.8 L) 5 cm above soil grade (A), at soil grade (B), or 5 cm below soil grade (C). Root collars were transplanted 5 cm above soil grade (A), at soil grade (G), or 5 cm below grade (B) into 36.6 L and subsequently to field (first letter= 10.8-L container planting depth, second letter= 36.6-L container planting depth third letter = field planting depth). The relation of the original root ball (2.6-L) to existing soil line is presented in brackets (cm). Relative Growth Rate (RGR) calculated according to Hoffmann and Porter (2002). Height measured from soil line to apex of tree. Means±standard error (n = 6).

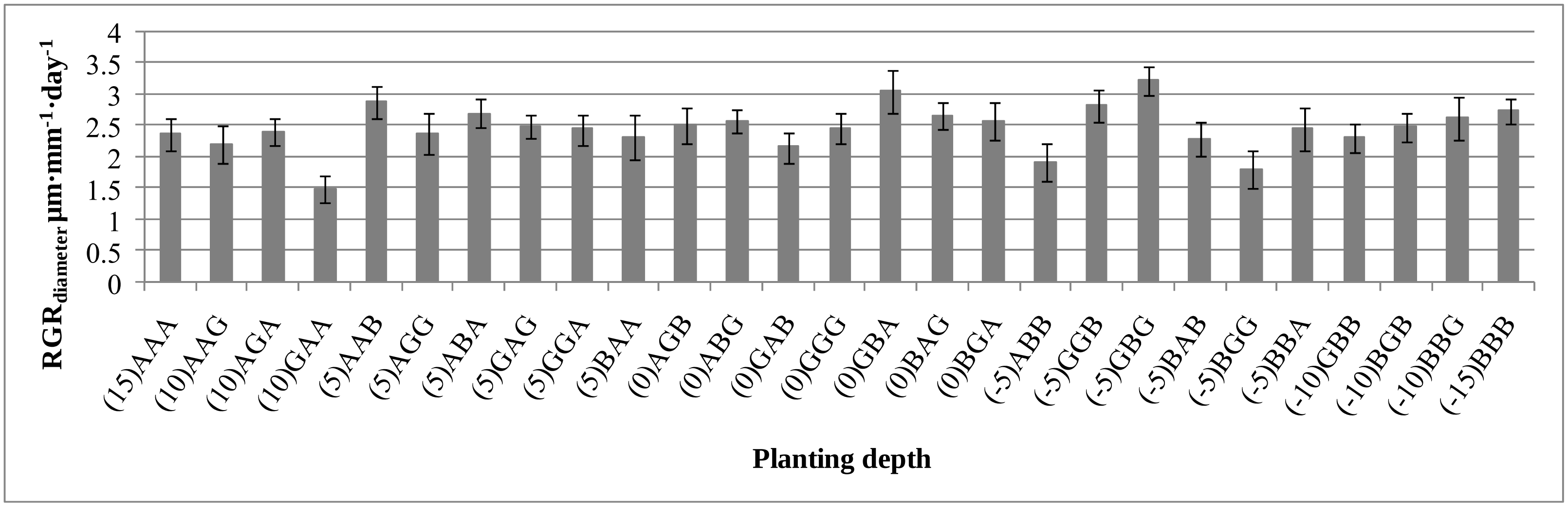

Fig. A.2. Effect of planting depth on relative growth rate in diameter ($RGR_{diameter}$) from March 2007-August 2007 in lacebark elm (*Ulmus parvifolia*) when initially transplanted (10.8 L) 5 cm above soil grade (A), at soil grade (B), or 5 cm below soil grade (C). Root collars were transplanted 5 cm above soil grade (A), at soil grade (G), or 5 cm below grade (B) into 36.6 L and subsequently to field (first letter= 10.8-L container planting depth, second letter= 36.6-L container planting depth third letter = field planting depth). The relation of the original root ball (2.6-L) to existing soil line is presented in brackets (cm). Relative growth rate (RGR) calculated according to Hoffmann and Porter (2002). Trunk diameter measured approximately 15 cm above existing substrate/soil line. Means±standard error (n = 6).

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Publications

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